# The Modeling of Fecal Coliform Bacteria in the North and South Rivers

by

Sumyee Sylvia Lee

B. Eng in Civil Engineering and Applied Mechanics
McGill University (1998)

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING
IN CIVIL AND ENVIRONMENTAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1999





Signature of the Author______________________________
Department of Civil and Environmental Engineering
May 13, 1999

Certified by______________________________
E. Eric Adams
Senior Research Engineer
Thesis Supervisor

Accepted by______________________________
Andrew J. Whittle
Professor of Civil and Environmental Engineering
Chairman, Committee for Graduate Studies

# The Modeling of Fecal Coliform Bacteria in the North and South Rivers

by

Sumyee Sylvia Lee

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Civil and Environmental Engineering
June, 1999

## ABSTRACT

A water quality model is developed and applied in the North and South Rivers for the North and South Rivers Watershed Association (NSRWA). The objective of this model is to investigate the response of the North and South Rivers to various fecal coliform sources and identify areas of the rivers that are most susceptible to pollution.

The model selected for water quality investigations in the North and South Rivers is RMA-11. RMA-11 uses velocity and depth outputs from the calibrated hydrodynamics model, RMA-10, as inputs. A simple test case is developed and the results show good agreement with the analytical solution. To calibrate the transport model, data from a dye study in the North River is used. Calibration involves the comparison of simulated and observed longitudinal spreading of the dye. Salinity is used to eliminate the effects of advection since measurements that share the same salt concentration are expected to represent the same point in the distribution. Of several diffusion coefficient options tested, the formulation that takes both velocity and element size into consideration is found to be the most appropriate. The model conserves mass well, as the increase in mass is insignificant when compared with values of any growth or decay rates.

In this study, existing fecal coliform data from various organizations are examined. Fecal coliform loading inputs into the rivers are quantified. Dry-weather fecal coliform sources into the rivers include wastewater treatment plant, waterfowl droppings, boat discharge, and dry-weather storm drain flow. Wet-weather sources are assumed to originate only from wet-weather storm drain flow.

The calibrated water quality transport model is used to simulate different fecal coliform loading situations. Although the fecal coliform model cannot be calibrated due to the lack of a consistent set of fecal coliform data, the simulated model results are similar to collected data. The development of a fecal coliform model has pointed out the need for future studies that examine contaminant sources in detail and provide consistent and accurate sets of fecal coliform data.

Thesis Supervisor: Dr. E. Eric Adams
Title: Senior Research Engineer

# Acknowledgments

First and foremost, I would like to thank Cameron for being an awesome project partner. I could not have done the project without his help. He is always patient when I have questions and in return, I laugh at his jokes.

I am very grateful to my thesis advisor, Dr. Eric Adams, for all his help and advice. He is (and will be) the only person who has (will) read my thesis more than once. As well, my warmest gratitude goes to Dr. Lew Thatcher, my project advisor, for his encouragement and support.

A special recognition needs to be made to Dr. Rocky Geyer of Wood Hole Oceangraphic Institute for allowing us to use his dye data. Without this contribution, this thesis would not have been possible. Furthermore, I would like to extend my sincere gratitude to Dr. Ian King for allowing us to use the RMA series.

To Steve Ivas and fellow NSRWAees, thank you for allowing us to raid your library and providing us with lots of information. I would also like to thank Ms. Elaine Dickinson for her assistance with boat loadings.

To my fellow M.Engers, thanks for an amazing year. In particular, I would like to thank Frédéric for being my chauffeur.

To Michael - my cook, editor, therapist, and friend - thank you for giving me perspective. Your love and enthusiasm for life is contagious.

Finally, I would like to thank my family - to my parents for their love and support - to my brother, Hon, for being a constant source of slicing, dicing, and chopping inspiration.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# 1. Background

## 1.1 Location

The North and South Rivers, located approximately 30 miles south of Boston, Massachusetts (Figure 1.1), wind through several suburban towns and discharge into Massachusetts Bay (Figure 1.2). The rivers are tidal in nature; the tidal head of the North River lies 20 kilometers upstream from the ocean and the tidal head of the South River lies 10 kilometers upstream. Together, the rivers share an inlet, known as New Inlet, located in Scituate, Massachusetts. The rivers form a complex estuary with changing geometry and flows, or hydrodynamics. In addition, marshland and wetland areas border the rivers.

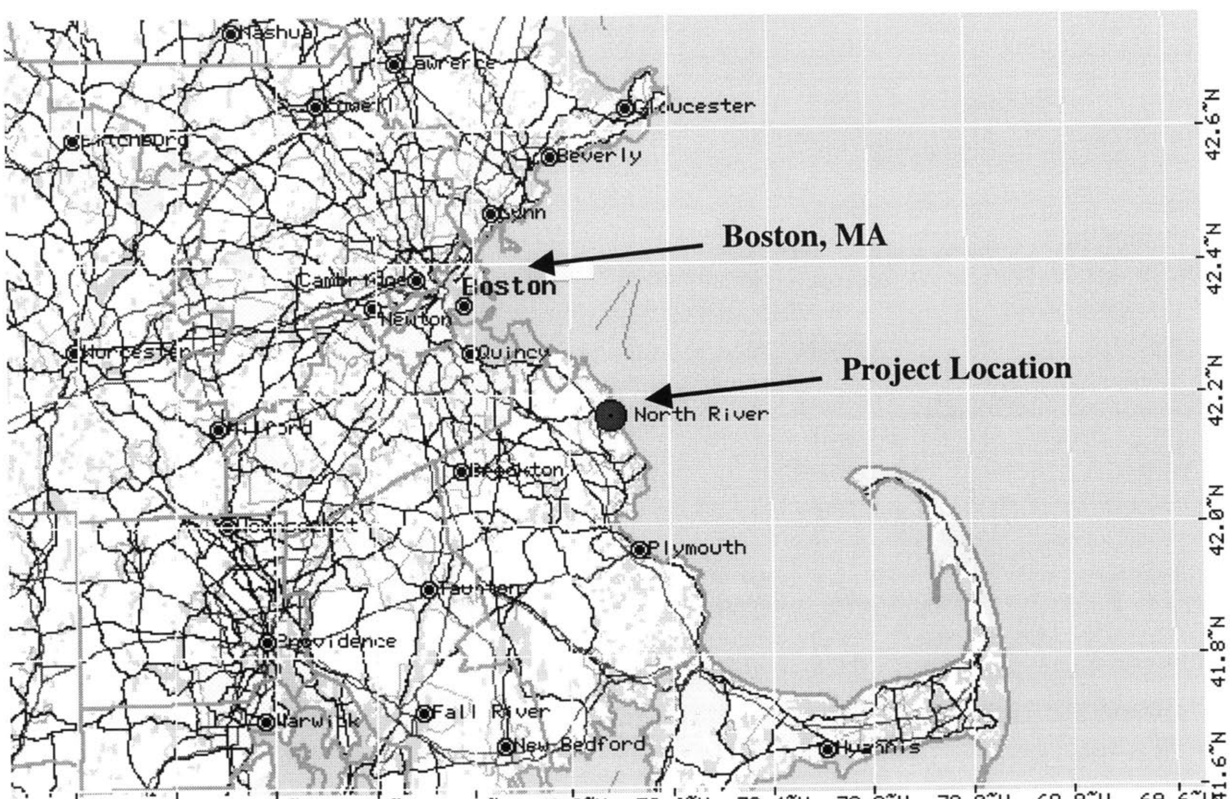



*Figure 1.1 Location of the North and South Rivers*

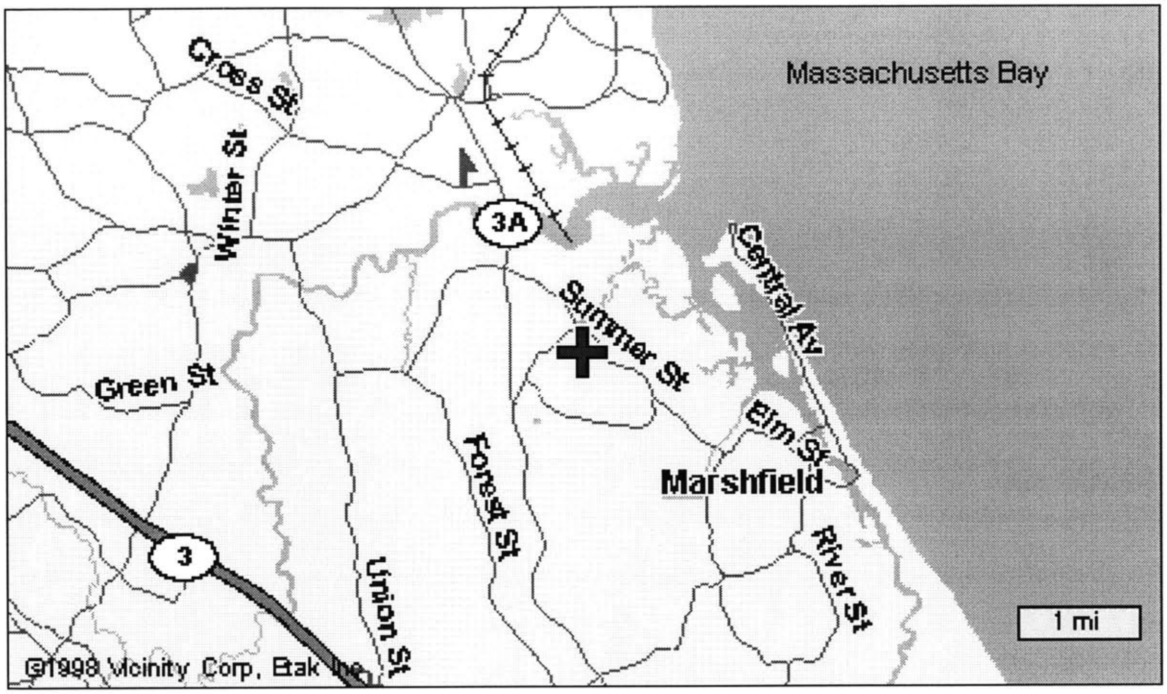



*Figure 1.2 Map of North and South Rivers*

## 1.2 Values of the Watershed

The North and South Rivers provide many intrinsic benefits to the communities through which they flow. Local residents take pride in the history of the North River as an important center of shipbuilding. Presently, recreational benefits include boating and swimming. The rivers also have the potential to support fishing and shellfish harvesting. Perhaps most importantly, the rivers provide a rich habitat for wildlife and a beautiful natural setting for residents and visitors.

## 1.3 The North and South Rivers Watershed Association

The North and South Rivers Watershed Association, Inc. (NSRWA) is a group of local citizens who are concerned with improving and preserving the unique watershed in which they live. In addition to organizing recreational events such as boating events and nature walks, NSRWA is active in evaluating water quality issues in the watershed. The

Association has commissioned the South River storm water investigations (1993) as well as water quality reports by Baystate Environmental Consultants (1990,1991). Currently, NSRWA is implementing the South River Initiative, which will focus attention on the water quality of the little studied South River. NSRWA also runs RiverWatch, which is a summertime water quality-monitoring program.

### 1.4 Water Quality Concerns

NSRWA is concerned with several water quality problems in the watershed. First, the Department of Marine Fisheries has closed shellfish harvesting beds due to high fecal coliform counts. Second, high quantities of fecal coliform present a health hazard to recreational users of the rivers. In general, NSRWA is concerned with how changes in water quality affect the ecological health of the rivers. These water quality concerns include other pollutants besides fecal coliform, such as nutrients.

### 1.5 Project Scope

To address the concerns of NSRWA, computer models capable of interpreting the water quality issues of the North and South Rivers have been developed. NSRWA will be able to use the models as tools to evaluate the response of the North and South Rivers to point and non-point pollution sources and identify areas of the rivers that are most susceptible to pollution.

This particular study uses the developed models to characterize fecal coliform contamination in the rivers. This involves quantifying the sources of fecal coliform in the watershed. The developed models calculate the effects of these estimated coliform loads on water quality in the rivers during the summertime. The summertime is the period of concern because recreational usage of the rivers is highest in the summer and past sampling has shown summer concentrations to be the higher than during other seasons.

## 1.6 Future uses of the models

NSRWA can use the models for proactive decision making in the management of the watershed such as:

- Warning residents and recreational users under what conditions the concentrations of pollutants may be high.
- Characterizing water quality in sensitive areas of the watershed including areas containing threatened species.
- Evaluating different pollution management plans and characterizing the resulting water quality improvements in the rivers due to the policies.
- Using the model as a visual educational tool to help residents, recreational users, business owners and developers understand the effect they have on the rivers.

## 1.7 Report Organization

The objective of this thesis is to develop a model to characterize fecal coliform contamination in the North and South Rivers. This thesis is the second part of the North and South Rivers modeling project (Tana and Lee, 1999). The first part of the project involves the companion hydrodynamics model and is discussed in detail in Tana (1999).

This thesis begins with a discussion on the computer model chosen and its governing equations in Chapter 2. Two simple cases developed to test the model are discussed in Chapter 3. Chapter 4 reviews the calibration and verification of the water quality transport model. The development of the fecal coliform model begins in Chapter 5 with an introduction. A review of all existing available fecal coliform data is located in Chapter 6. Chapter 7 considers all possible fecal coliform sources and evaluates their impact on the North and South Rivers. Fecal coliform decay rates are briefly discussed in Chapter 8. Several fecal coliform loading scenarios are simulated in Chapter 9. The conclusion and some recommendations are located in Chapter 10.

# 2. Review of RMA-11 Model

RMA-11 (King, 1997) is a finite element water quality model for simulation of three-dimensional rivers, estuaries, and bays. The model is chosen for several reasons. First, RMA-11 is designed to accept input of velocities and depths from RMA-10, a hydrodynamics model (Tana, 1999). Second, in addition to the transport, the modeling of fecal coliform requires a model that takes into consideration the ultimate fate of the constituent. RMA-11 models coliform fate using three loss parameters (King, 1997). Third, it is also capable of simulating one, two, or three-dimensional approximations.

Although RMA-11 accepts results in the form of velocities and depths from RMA-10, RMA-11 operates independently of the RMA-10 time discretization. RMA-11 automatically interpolates velocity and depth inputs for the times specified.

## 2.1 Governing equations for two dimensional depth averaged transport

Since the modeling of North and South Rivers estuary is mostly in two dimensions, two-dimensional depth-averaged transport equations are most appropriate. These equations are obtained by integrating over the vertical (King, 1997).

### *2.1.1 Continuity equation*

The depth-averaged continuity equation is as follows:

$$h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}+\frac{\partial h}{\partial t}-q_i=0 \qquad (2.1)$$

where $q_i$ = inflow per unit area
x, y, z = Cartesian coordinate system
u, v, w = velocities in the x, y, z directions
h = water depth

*2.1.2 Transport equation*

To model fecal coliform and other water quality constituents, the governing equation is the advection-diffusion equation. The following is the depth-averaged transport equation:

$$\frac{\partial c}{\partial t}+U\frac{\partial c}{\partial x}+V\frac{\partial c}{\partial y}-\frac{1}{h}\frac{\partial}{\partial x}\left(D_x h\frac{\partial c}{\partial x}\right)-\frac{1}{h}\frac{\partial}{\partial y}\left(D_y h\frac{\partial c}{\partial y}\right)-kc-\theta_s=0 \qquad (2.2)$$

where $D_x$ = diffusion coefficient in x direction
$D_y$ = diffusion coefficient in y direction
k = first order decay
$\theta_s$ = source and sinks of water quality constituent
c = concentration of water quality constituent

*2.1.3 Water quality parameters governing equations*

Each water quality constituent has its own growth and decay governing equations. The reader is referred to King (1997) for more information. For the case of fecal coliform, a detailed discussion can be found in Chapter 8 and Appendix C.

Rate coefficients in the source/sink terms are temperature-dependent. The input coefficients are initially at 20°C and then corrected to the actual temperature using the following equation:

$$X_t = X_{20}\,\theta^{(T-20)} \qquad (2.3)$$

Where $X_t$ = coefficient at computed temperature
$X_{20}$ = coefficient at 20°C
$\theta$ = empirical constant for each reaction coefficient

## 2.2 Finite element method

The finite element structure of RMA-11 is identical to RMA-10. RMA-11 uses the finite element method to numerically approximate solutions to the above equations. The steps of the approach used by RMA-11 is as follows:

1. RMA-11 defines elements by isoparametric approximations.
2. RMA-11 uses the Galerkin Method of Weighted Residuals for the finite element derivation.
3. RMA-11 uses the Newton Raphson method for equation structure and iteration of nonlinear terms.
4. RMA-11 uses a modified Crank Nicholson time stepping scheme for unsteady flow.
5. RMA-11 integrates finite element element integrals using Gaussian quadrature.

The reader can find more details in King (1993).

## 2.3 Parameters

RMA-11 has several input components:

1. Velocity and depth outputs from the hydrodynamics model, RMA-10
2. Constituent loadings into the body of water
3. Constituent source/sinks

The output of the model is the concentration of constituent at different times and locations.

The advective movement of the rivers is presented in Tana (1999). To calibrate the transport of contaminants, the turbulent diffusion coefficients ($D_L$, $D_T$) are used. These values are adjusted until the values in the model are similar to actual data. A detailed discussion of method and result of calibration is located in Chapter 4.

# 3. Simple Test Cases

To gain a better understanding of the model and to ensure that the model performs calculations correctly, two simple test cases are devised. The constituent modeled is conservative dye. Each test case involves a simple rectangular channel with a constant depth.

The rectangular channel is divided into 40 square grid cells, with two rows of 20 square grids. Each grid cell has a length and width of 50 meters. Therefore, the channel is 1000 meters in length, 100 meters in width and 1 meter in depth. A constant velocity of 0.05 m/s and a constant diffusion coefficient of 4 $m^2/s$ are used. The test scenarios are run under two alternative conditions: instantaneous loading and continuous loading

## 3.1 Instantaneous loading

An instantaneous loading exercise is performed to verify that the amount of loading input corresponds with the actual amount of mass in the system. With a time step of 0.125 hour, or 450 seconds, an instantaneous loading of 100,000 grams/sec is released in the beginning of the channel (x=0). The model calculates a total mass of $4.38549 \times 10^7$ grams of dye in the system at 2.5 hours (or 9000 seconds), which is very similar to the actual value of $4.5 \times 10^7$ grams. This simple test case reveals that the model gives the correct amount of loading input.

## 3.2 Continuous loading

The purpose of this test is to ensure that the output concentrations from RMA-11 correspond to the appropriate analytical solution. The governing equation for a one-dimensional, continuous contaminant source with a constant diffusion coefficient, no decay, and specified concentration at x=0 is:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = E\frac{\partial^2 C}{\partial x^2} \tag{3.1}$$

The corresponding transient-state analytical solution is as follows:

$$C = C_o\left[0.5\cdot\exp\left(U\cdot\frac{x}{E}\right)\cdot erfc\left[\frac{(x+U\cdot t)}{2\cdot\sqrt{E\cdot t}}\right]\right] + \left[0.5\cdot erfc\left[\frac{(x-U\cdot t)}{2\cdot\sqrt{E\cdot t}}\right]\right] \tag{3.2}$$

A continuous concentration input of 100 mg/L is injected at the beginning of the channel (x=0) as shown in Figure 3.1. The dye is loaded as a boundary condition concentration formulated by RMA-11. The boundary conditions for both analytical and numerical solutions are:

$C = C_o$ at $x = 0$

$C = 0$ at $x = \infty$

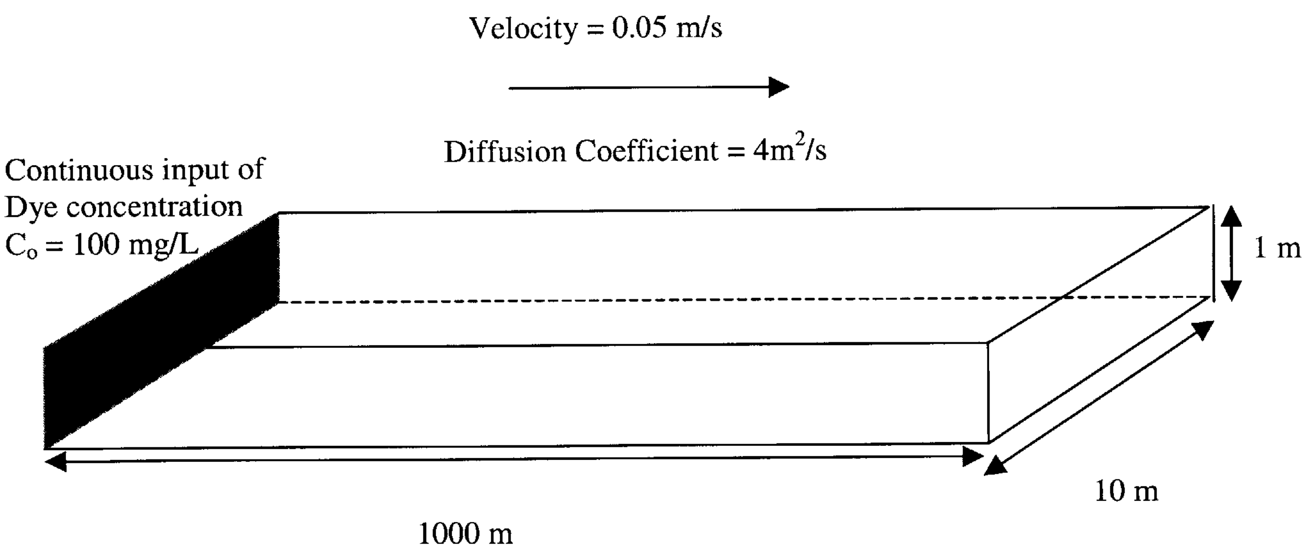



*Figure 3.1 Test Case Configuration*

The results of the model simulation at 2.5 hours and the corresponding analytical solution are shown in the following plot (Figure 3.2). The two solutions match very well. The result of this graph shows that RMA-11 performs the calculations correctly and can be used further to develop the model for different fecal coliform scenarios.

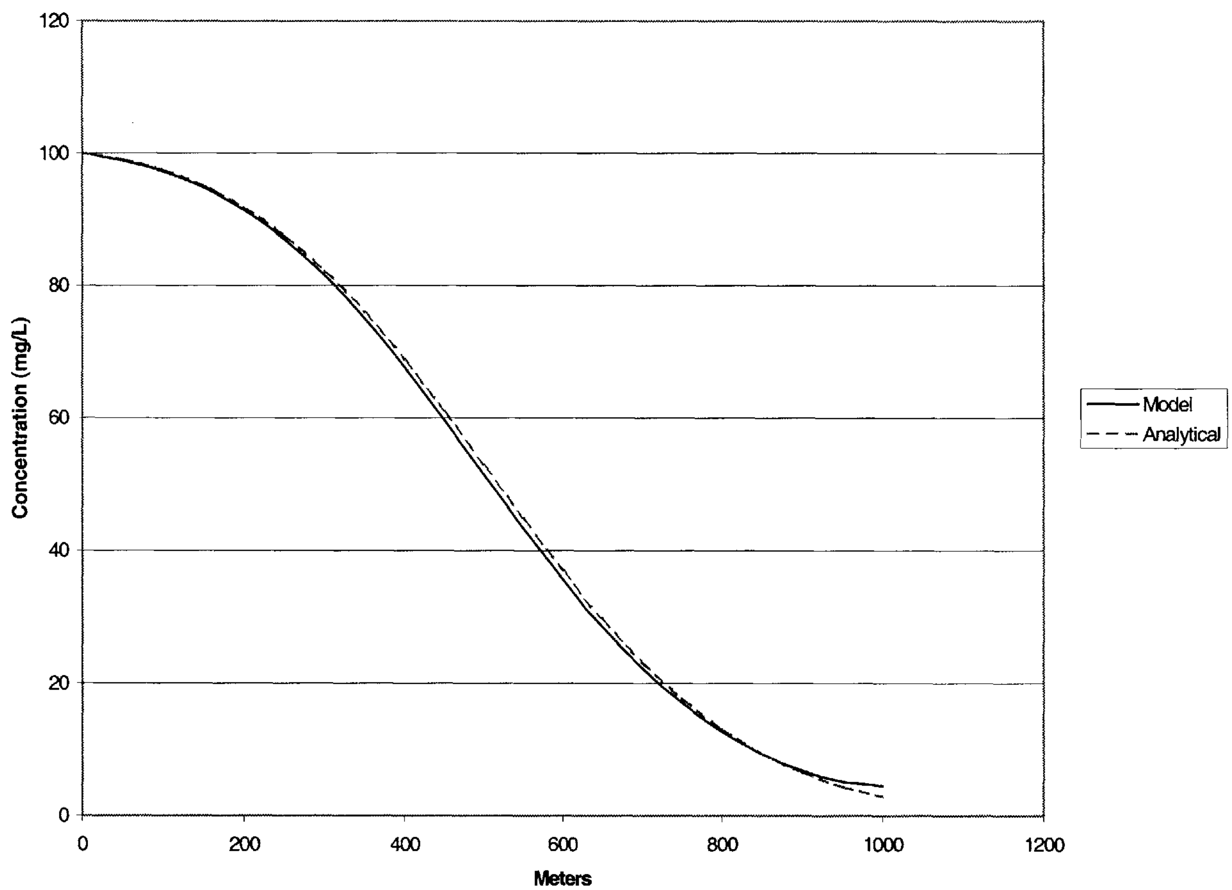



*Figure 3.2 The comparison of model result and analytical 1-D solution at 2.5 hours*

# 4. Water Quality Model Transport Calibration

Model calibration is the testing and tuning of a model and requires a consistent and rational set of field data (Thomann and Mueller, 1987). A set of data from a dye experiment performed in July 1997 by Dr. Rocky Geyer at Woods Hole Oceanographic Institute (WHOI) is used to calibrate the dispersive transport of the North and South Rivers. Although the objective of this study is to simulate fecal coliform, dye is a more appropriate constituent for model transport calibration because it is conservative and the calibration would focus on advection and dispersion without decay.

## 4.1 Dye study

### *4.1.1 Experiment*

Data collection spanned over five days beginning on July 14, 1997. On day 1 (July 14), ambient dye concentrations were measured throughout the North River. In general, the ambient concentrations were below detectable levels. The two dye releases took place on day 2 (July 15), and day 4 (July 17). For each dye release, 4.5 kg of conservative, fluorescent Rhodamine WT dye was instantaneous injected evenly across the width of the estuary. The first release took place at approximately 9:20 am and 10.8 km upstream from the mouth (Figure 4.1). The second release was injected at approximately 8:20 am and 7.8 km upstream from the mouth near Bridge Street (Figure 4.1). After each dye release, dye concentrations and salinity measurements were recorded throughout the estuary for two days.

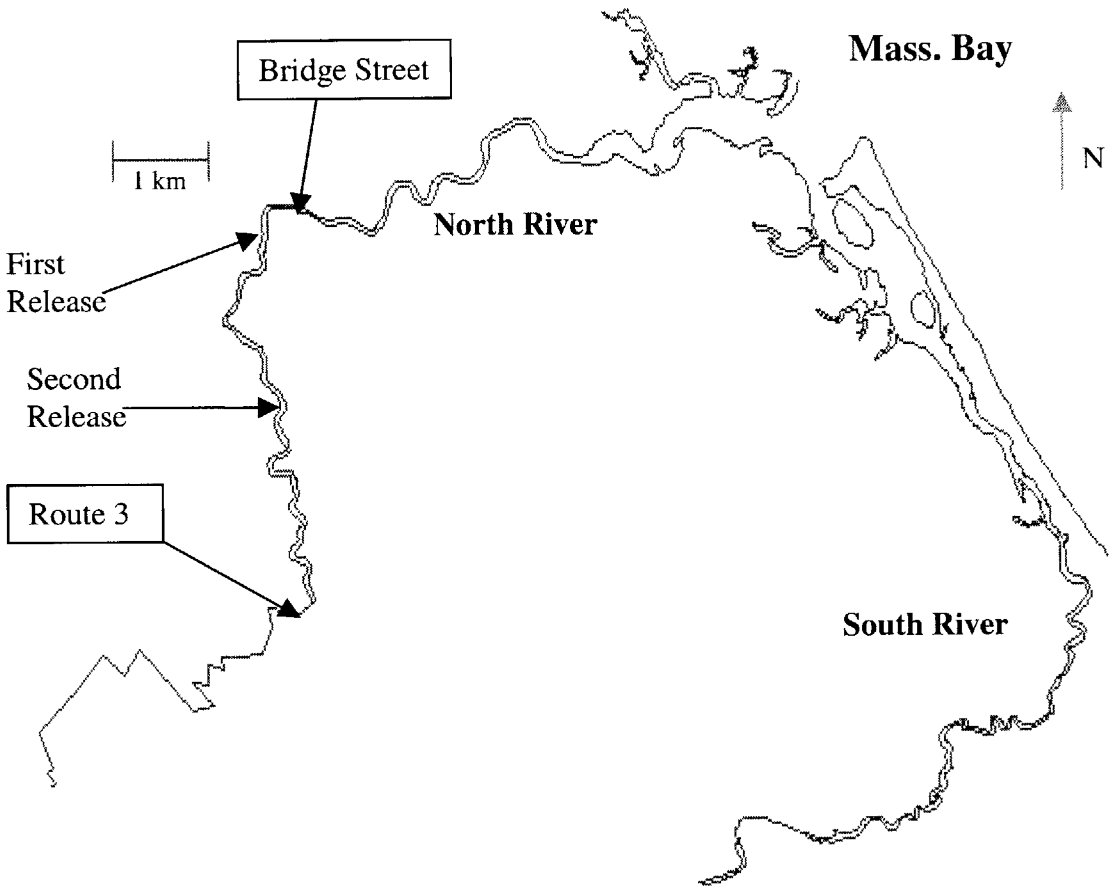



*Figure 4.1 Location of dye releases*

### *4.1.2 Manipulation of Dye Data*

The objective is to calibrate and validate diffusive transport in the model using Dr. Geyer's dye study results. To accomplish this, one must compare the measured longitudinal spread of the dye in the river with the simulated longitudinal spread of a conservative substance in the model. Because the North River is part of an estuary system with complex hydrodynamics, this is not a straightforward task. The immense amount of collected data requires manipulation to allow for a direct comparison with the model.

The extent of dye spreading 24 hours after release is used for comparison. Dr. Geyer released the dye in the morning of day 2 and took the last measurements to characterize the extent of dye-spreading the next morning. These data from the next morning that characterize a 24-hour spread of the dye are used for comparison with a 24-hour spread of dye in the model. This spread includes dispersion processes over two tidal cycles. However, Geyer could not measure an instantaneous spread of the dye with only one boat. While he took measurements over several hours, the tide transported the dye by advection at a different rate from the movement of the boat.

Since the hydrodynamics model already deals with the advection of the dye, this exercise is concerned with the spread of the dye only. To eliminate advection effects and get an equivalent to the instantaneous 24-hour spread, salinity data are used. As mentioned previously, each dye measurement is accompanied by a salinity measurement. Since the salt transport tracks the tidal advection, measurements that share the same salt concentration should represent the same point in the distribution. Differences in salinity between two measurements represent differences in distance in a stationary reference because salinity can serve as a tracer for the tidal flow.

The conversion from salinity to an equivalent distance requires a salinity gradient. Since the measurements are from a high tide period, the salinity gradient (dS/dx) at high tide from Bridge Street to Route 3 Bridge is calculated (Equation 4.1). The salinity gradient is assumed to be linear. Dr. Geyer provided salinity data at these two locations, which consist of hourly salinity measurements.

For each data point, the measured salinity (S) is divided by the salinity gradient (dS/dx) and an effective distance ($X_{eff}$) is calculated.

$$X_{eff} = \frac{S}{dS/dx} \tag{4.1}$$

Dye concentrations at each data point is then plotted against this effective distance, which results in the following graph (Figure 4.2) for the first dye release. It is assumed that there is little spreading of dye or salt over the period of measurement (frozen cloud assumption) so this method gives an equivalent to the instantaneous distribution against longitudinal distance. The graph displays a near Gaussian distribution that shows how much the dye is dispersed over 24 hours.

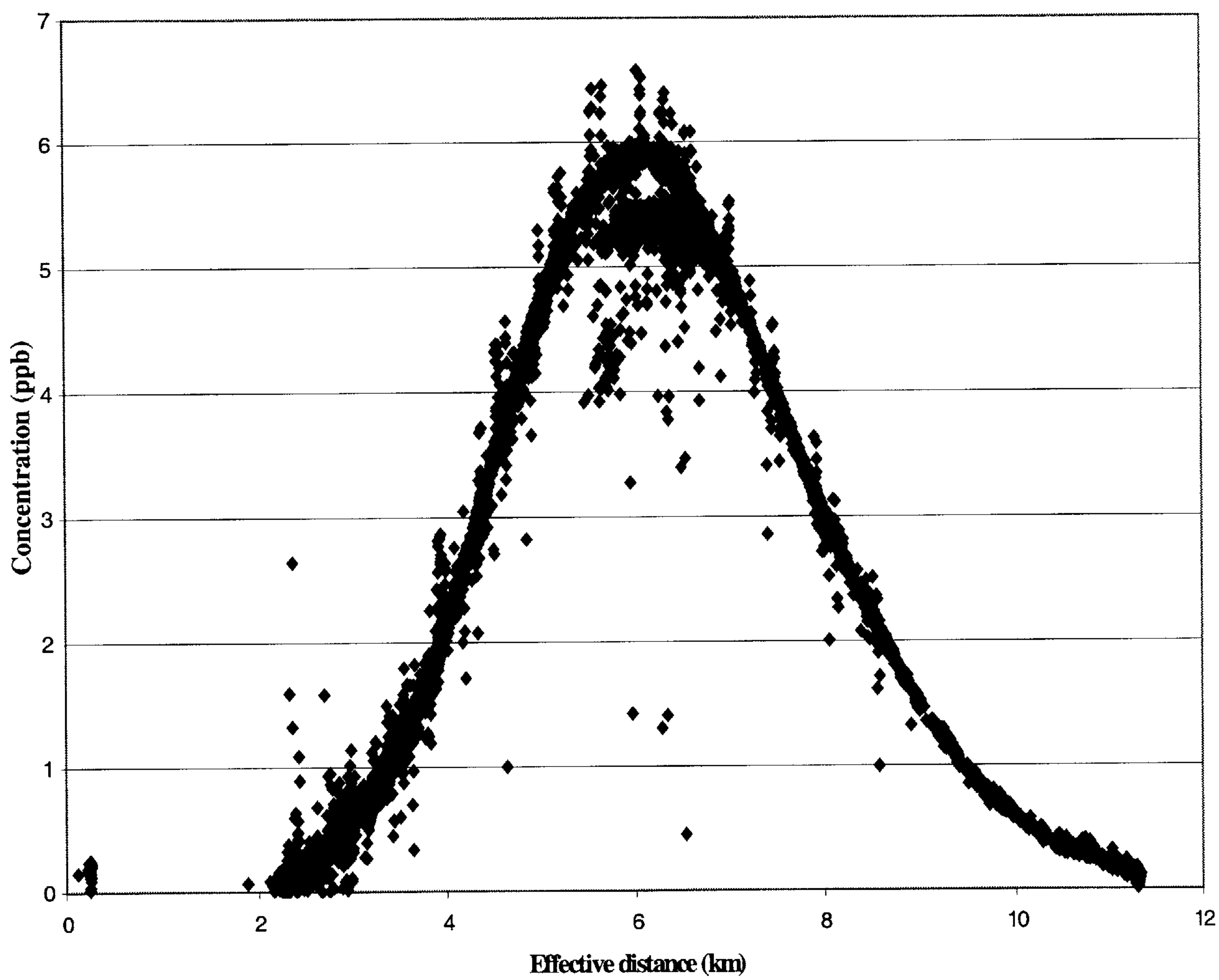



Figure 4.2 The effective dispersion of dye (1st release)

*4.1.3 Longitudinal Dispersion*

The purpose of Geyer's study was to measure the longitudinal dispersion in the North River. Dispersion is the spread resulting from differential advection and diffusive mixing. In estuaries, tides, trapping, and density-driven circulation can enhance dispersion (Geyer and Signell, 1992). Longitudinal dispersion represents the mixing results of differential velocities in the vertical and transverse direction.

Geyer's study is appropriate for comparison to this application of RMA-11 because the study area is modeled as essentially one-dimensional. One element defines the width of the river, and although three nodes can represent the transverse velocity profile, these nodes do a poor job of resolving the differential advection. The longitudinal spread that occurs can be best described by a longitudinal dispersion coefficient because the vertical velocity profile is not resolved and the transverse profile is poorly resolved. A calibration tool representing longitudinal dispersion best represents physical mechanisms that cause spreading.

## 4.2 RMA-11 model

*4.2.1 Assumptions*

To develop the numerical model, several assumptions are made. First, all initial concentrations of dye are zero. Thus, all background dye concentrations are ignored. Second, it is also assumed that the dye was injected evenly across the width of the river and that the dye is conservative.

*4.2.2 Data input*

Since Dr. Geyer and his investigators released the dye evenly across the river, two narrow elements are added to the existing schematization to mimic the initial injection pattern.

The dye is loaded in these newly created elements as an elemental loading of $1.25 \times 10^5$ grams/second for 36 seconds, which gives a total of 4500 kg of dye. However, the actual amount of dye injection was only 4.5 kg. A factor of 1000 is multiplied to the elemental loading because the concentration outputs (mg/L) in RMA-11 only have 3 decimal places and the dye concentrations decrease rapidly. In general, dye concentrations are in the magnitude of ppb's or 0.001 mg/L. The increase in accuracy due to the factor allows for better comparisons with actual data.

Results from the hydrodynamics RMA-10 model are used as an input file. The velocity and depth results are from the spatially variant Manning's n scheme (Scheme 2) without flats (Tana, 1999). A time step of 0.05-hour (3 minutes) is used throughout the simulation, except when the dye is released. When the dye is released, the time step is decreased to 0.01-hour (36 seconds) as it better represents the actual dye release and gives more reasonable results. Dye is injected in the model at the same time and place as the actual experiment.

### *4.2.3 Diffusion coefficients*

Diffusion coefficients are the major set of parameter used to calibrate the water quality model. The longitudinal diffusion coefficient is of the most concern and transverse diffusion coefficient is of secondary importance. In particular, since the dye is injected as an elemental loading, it is well mixed in the lateral direction. However, RMA-11 requires a transverse diffusion coefficient input regardless. Furthermore, although a lateral coefficient is not important for the purposes of dye calibration, it may become important once the calibrated model is applied to the modeling of fecal coliform in Chapter 5.

RMA-11 allows for 6 different methods of specifying diffusion coefficients. Three methods are chosen for comparison to determine the most appropriate method for application.

The first option (IDIFF=0) provides the simplest method. This allows for direct value inputs of the diffusion coefficient in the global X and Y directions. In this instance, X represents the East-West direction and Y the North-South. This method does not correspond to typical formulations of dispersion in rivers. Furthermore, while the North River runs in the direction North-South upstream, it takes a dramatic 90° turn in the East-West direction as it approaches the mouth. This unique geometry restricts the possibility of using a diffusion coefficient in the global X and Y directions. The X and Y directions rarely match up with the longitudinal and transverse directions of the river as the river meanders throughout. Despite the aforementioned problems, a trial with horizontal and vertical coefficients of 15 $m^2/s$ and 1.5 $m^2/s$ is simulated. Surprisingly, the results from this trial compare well with actual data. Another trial with equal horizontal and vertical coefficients is also simulated to ensure the direction of flow always has the same coefficient. A coefficient of 5 $m^2/s$ is found to match well with actual data. Realistically, however, this method does not accurately represent the dispersion of the North River and may not be well extrapolated to other reaches of the river and other time spans.

Unlike the first option, the second option (IDIFF=4) involves diffusion coefficients in longitudinal and transverse directions. This option is more appropriate for real rivers in the natural world as most do not have a constant straight-line geometry. Since dispersion depends on the geometry of the river, this application is more realistic.

The longitudinal diffusion coefficient is obtained from scaling an input value by element size whereas the transverse coefficient is a factor of the longitudinal value. Element size scales the size of the turbulent eddies available for mixing. Since longitudinal dispersion results partially from mixing over the depth and the width, a substitute for element width helps scale the amount of mixing. The transverse diffusion coefficient is given a factor of 0.1 to the longitudinal diffusion coefficient throughout the North River, except near the confluence where the factor is 1.0. Complex hydrodynamics near the river mouth cause the area to be well-mixed, whereas in the main stretch of the river, longitudinal diffusion dominates. A factor of 10% for transverse diffusion is a typically accepted value

(Adams, 1999). The estimate of 0.15 as an input value works well, as the results in this simulation are very similar to the actual data.

Similar to option 2, the last option (IDIFF=1) involves diffusion coefficients in longitudinal and transverse directions only. This option is the most complex of all options and is the most appropriate method because it takes both element size and velocity into consideration. The longitudinal coefficient is computed from element size and velocity magnitude, scaled by an input value. This accounts for both of the major scaling factors of longitudinal dispersion. In fact, velocity may be the more important factor because differential advection causes longitudinal dispersion. With higher velocities, the differential advection is greater and the longitudinal spread is increased. Similar to option 2, the transverse coefficient is a factor of the longitudinal value. A constant transverse value of 10% of longitudinal diffusion coefficient is used throughout the North River, except near the confluence. Several trials with different scaling input values are simulated and it is determined that an input value of 0.45 is the most appropriate.

The remaining three options in RMA-11 are similar to the ones discussed in this chapter. However, they are more concerned with the manipulation of the transverse diffusion coefficient. Since transverse diffusion is of secondary importance in the North River, these options are not examined and evaluated.

### *4.2.4 Model results*

The first dye release is simulated for 47 hours in all cases and the results are shown in Figure 4.3. The concentrations shown on the graphs are the average concentrations on the second day (day 3). All three different options appear to give similar results. However, since option 3 is the most appropriate approach as it takes both velocity and element size into consideration, results from option 3 will be used for calibration.

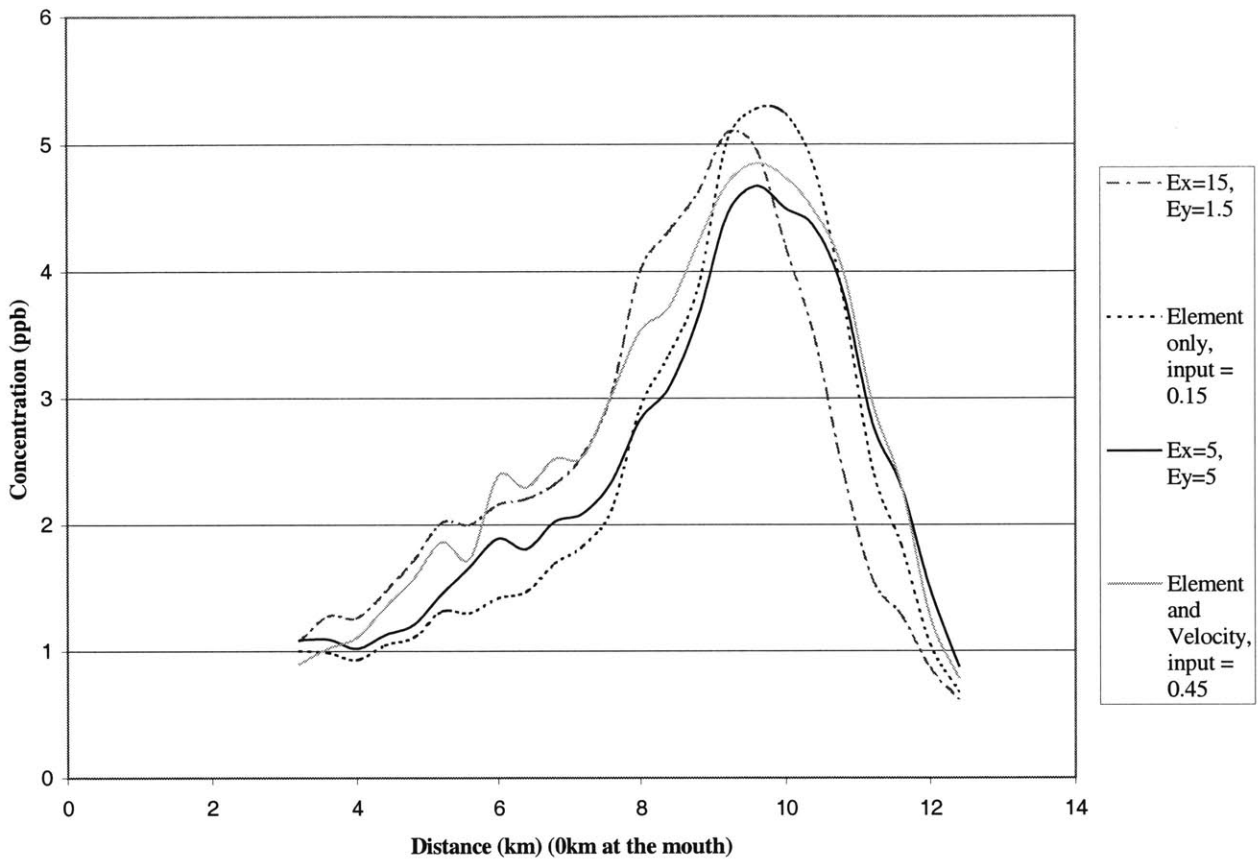



*Figure 4.3 Results from different methods of specifying diffusion coefficients in RMA-11*

### 4.3 Actual vs. Model comparison

When the effective distance is calculated, it is highest where the salinity is the highest (Equation 4.1). Therefore, the location at the mouth has the highest effective distance. However, the model is set up such that at the mouth, the distance is zero. To ensure that the data and the model results use the same reference point, the model results are switched to the same reference as the actual data.

Figure 4.2 and the modified option 3 curve from Figure 4.3 are overlapped to obtain Figure 4.4. With the exception of the upstream end of the curves, the two graphs match very well. The discrepancy at the end of the curves may be due to several factors. First, near the confluence of the river, there are complex hydrodynamics issues that have not yet been resolved. Second, since the salinity gradient was obtained only from Bridge Street to Route 3A Bridge, it can be expected that results from outside those regions may be less accurate.

Aside from the visual comparison of the two curves, a numerical comparison can also be made. The standard deviations of the two curves are calculated. The standard deviation ($\sigma$) of the actual data curve is 3.0 km whereas the standard deviation of the model curve is 3.4 km. The difference can be attributed to the end of the curves where the two separate. Overall, however, the two curves are very similar and the water quality portion of the model is calibrated.

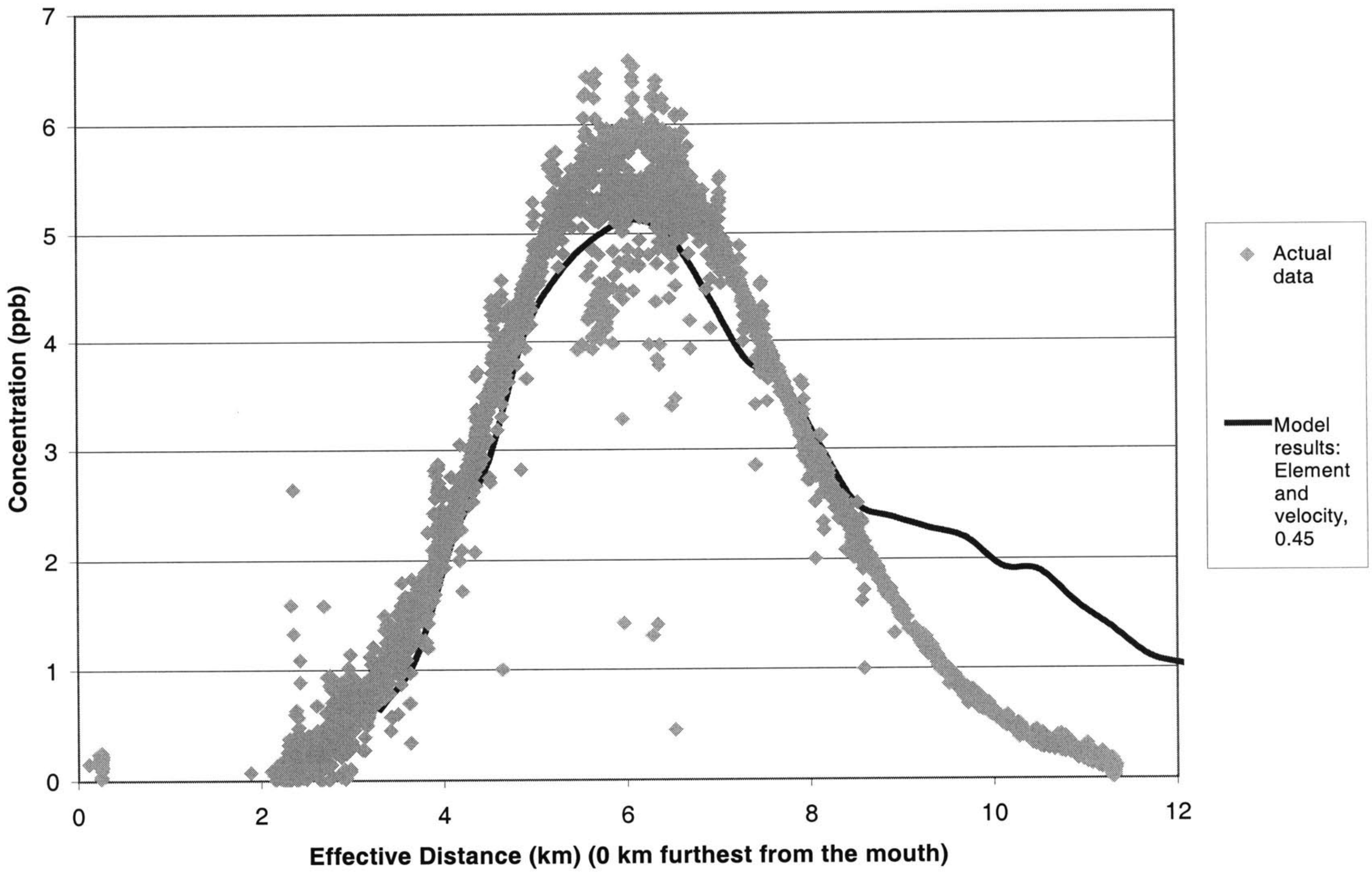



*Figure 4.4 Calibration Curve*

### 4.4 Model verification

To verify the water quality model, the second dye released is used. Option 3 of the diffusion coefficient (IDIFF=1) with an input value of 0.45 is again used and Figure 4.5 is a display of the model results when compared to actual data. Again the extent of spreading 24 hours after the release is compared. Although the two curves do not appear to match very well, the comparison is still reasonable. Compared with the results from the first survey, these results are more complicated by several factors.

First, since the direct input of initial concentration in RMA-11 is not possible, the residual dye concentrations from the first dye release must be obtained from the modeled first dye release. Any discrepancies between the modeled results and actual data from the first dye release will be compounded in the second dye release. Second, this total amount of mass simulated in RMA-11 increases slightly as time increases (Chapter 4.5). After a 4-day simulation, the additional mass becomes a higher portion of the total mass and contributes to a further increase in dye concentrations.

The formulation accounting for both velocity and element size clearly outperforms the other formulations for several reasons (Figure 4.5). The dye injection was placed in the North River at a different location. First, the relationships between the global axis and the longitudinal direction of the river are different so the application of the first option fails. Second, the dye travels through areas with different cross-sections so the turbulent eddies that induce mixing have different sizes. Therefore, including the element size helps the performance. Most importantly however, Dr. Geyer injected the dye at different times in the tidal cycle. The first injection took place at high tide slack water, while the second injection took place at flood tide. The velocities, and therefore the differential advection, are greater at the start of the second release than the first release. The start is when the gradients of concentration are the greatest so spreading is greatest at that time. Since the differential advection is stronger for the beginning of the second release, more spreading is expected. The inclusion of velocity as a scaling factor accounts for these differences. The formulation with both element size and velocity is the best formulation for extrapolation to different spatial and temporal situations.

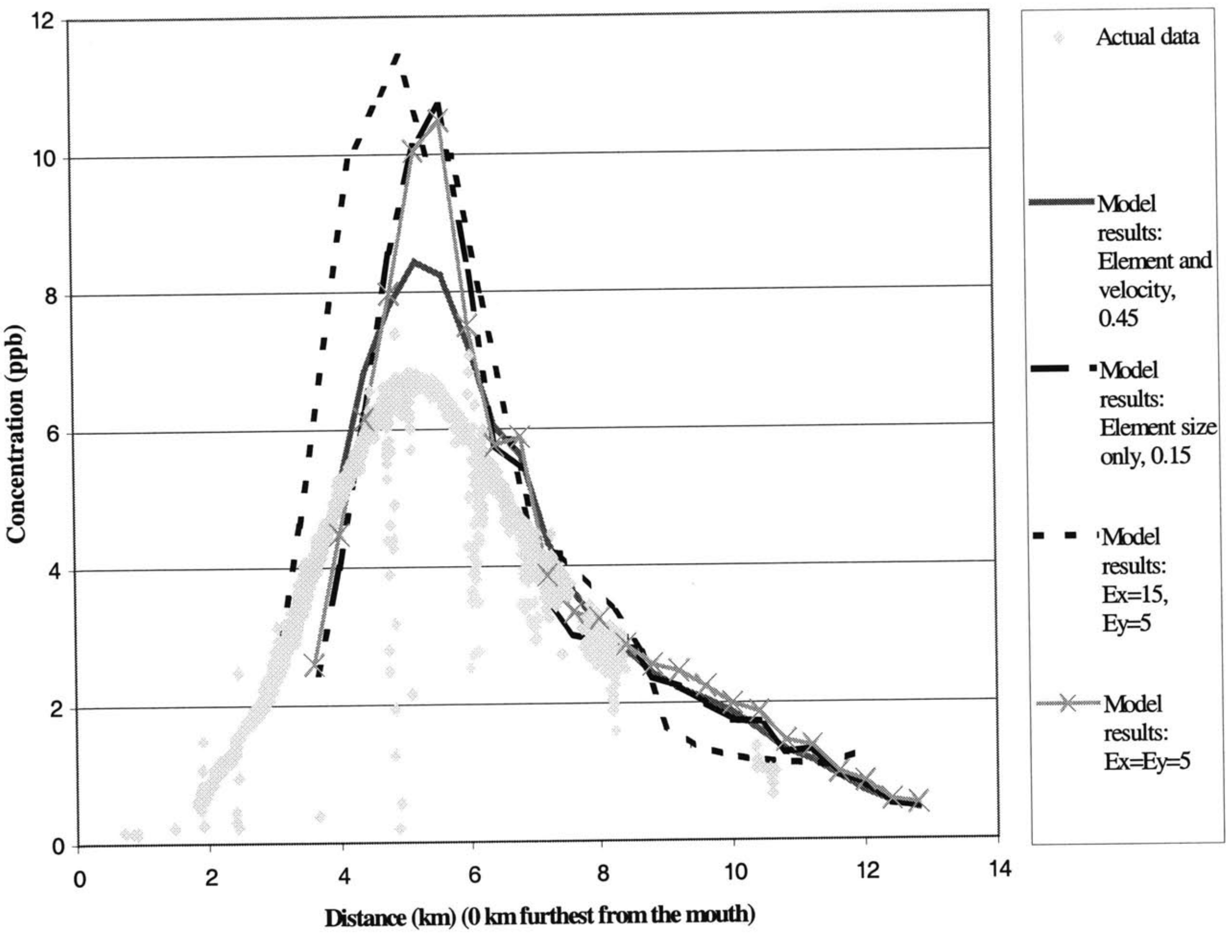



*Figure 4.5 Comparisons of diffusion coefficient options in RMA-11 for model verification*

### 4.5 Conservation of mass in RMA-11

With any finite element model, the conservation of mass is an important issue. As expected, the total mass of injected dye gradually increases over the modeled time period. However, with close inspection, it can be recognized that the numerically added mass is a small percentage of the total mass. As indicated in Figure 4.6, the total amount of mass released is 4.5 kg and results from RMA-11 model show an increase to 4.69 kg after 47 hours. This represents only a 4.2% increase and corresponds to a first order growth factor of only 0.021/day.

Because this growth rate is small when compared with the absolute values of any decay or growth rate describing water quality constituents of interests (e.g. $k \approx 1$ /day for bacteria), the lack of absolute mass conservation is considered insignificant.

Similarly, after the second dye release, the increase in mass is not significant. The total amount of mass after both dye releases is 9 kg but results from RMA-11 model show an increase to 9.83 kg in 87 hours. Using the same method described above, this represents a first-order growth factor of only 0.024/day.

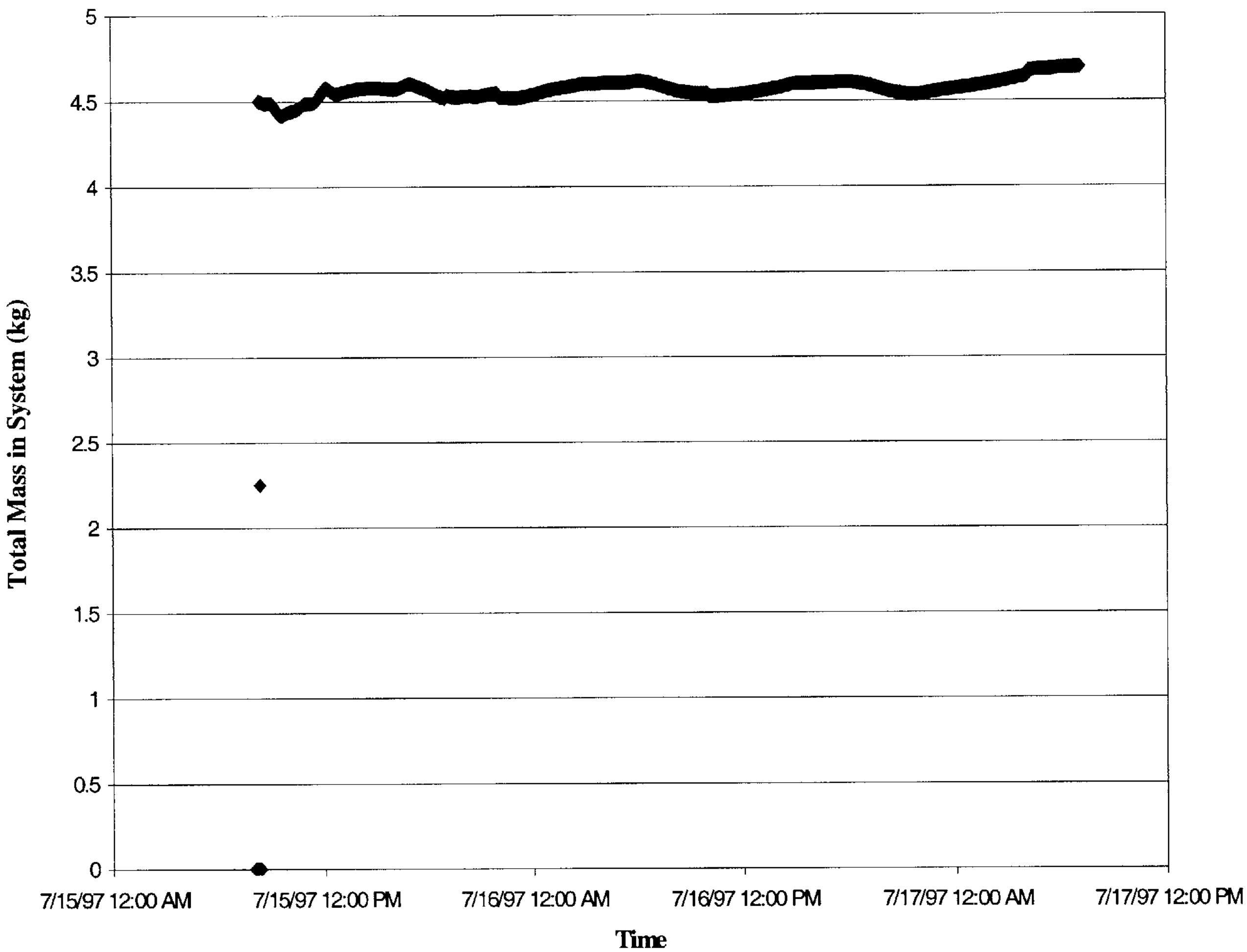



*Figure 4.6 Mass Conservation in RMA-11 (1st dye release)*

# 5. Fecal Coliform Modeling

The calibrated water quality model is now ready for application to actual constituents. Fecal coliform bacteria are selected as the constituent to model as a result of NSRWA's concern over bacterial contamination and its adverse effects on the water quality of the rivers.

## 5.1 Fecal Coliform bacteria

Fecal coliform bacteria are organisms found in the intestinal tract of humans and other animals. The presence of pathogenic organisms is often used as an indicator of the microbiological quality of water. Fecal coliform is a nonpathogenic organism abundant in human and animal waste and its presence indicates that other pathogens may also be present. Measuring individual pathogens is usually not practical because the methods are generally expensive, difficult and not always quantitatively reproducible (Hammer and Hammer, 1996). For these reasons, fecal coliform bacteria are employed as indicator organisms for these pathogens since they share similar habitats. Testing for fecal coliform requires an elevated temperature of 44.5°C such that the growth of other non-fecal bacteria is suppressed (Chapra, 1993).

Pathogenic bacteria, viruses and parasites have an adverse impact on the following water uses (Thomann and Mueller, 1987):

1. Drinking water
2. Primary recreational contact (i.e. swimming and bathing)
3. Secondary recreational contact (i.e. boating and fishing)
4. Shellfish harvesting

## 5.2 Fecal Coliform Concerns in North and South Rivers

Although the North and South Rivers are not sources for drinking water, the rivers are heavily used for primary and secondary recreational pursuits, especially during the summer months. As well, the North and South Rivers are home to many shellfish beds that are affected by the high fecal coliform counts.

For many years, NSRWA has used fecal coliform as an indicator of the water quality of the rivers. Specifically, since the limit for fecal coliform in shellfish is much lower than the limit for contact recreation purposes [14/100 milliliters (mL) vs. 100/100mL], shellfish coliform counts are used as the baseline indicator for the overall health of the river. In fact, over 450 acres of shellfish habitat are closed on the South River and over 150 acres are closed on the North River due to high fecal coliform counts.

The closure of such large areas of shellfish beds is of great concern since commercial shellfish harvesting is economically beneficial to the region. Although the exact figure for loss revenue due to closed shellfish beds in the area is not known, shellfish harvesting is a $70 million industry in Massachusetts alone (Metcalf and Eddy, 1995). Maps of the historical and present shellfish distribution in the North and South Rivers are located in Figures 5.1 and 5.2.

As well, fecal coliform concentrations have been shown to exceed acceptable limits for recreational activities at locations such as Willow Street Bridge on South River at certain times of the year. It is important that residents are protected from being exposed to pathogenic bacteria and viruses.

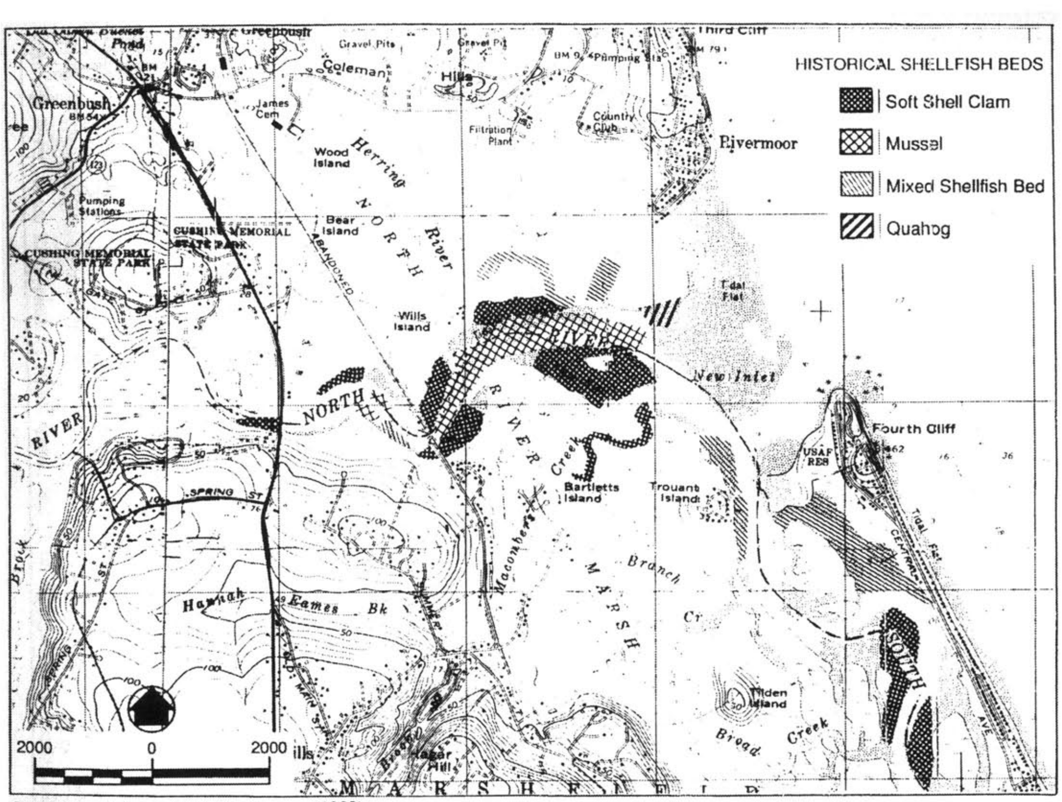
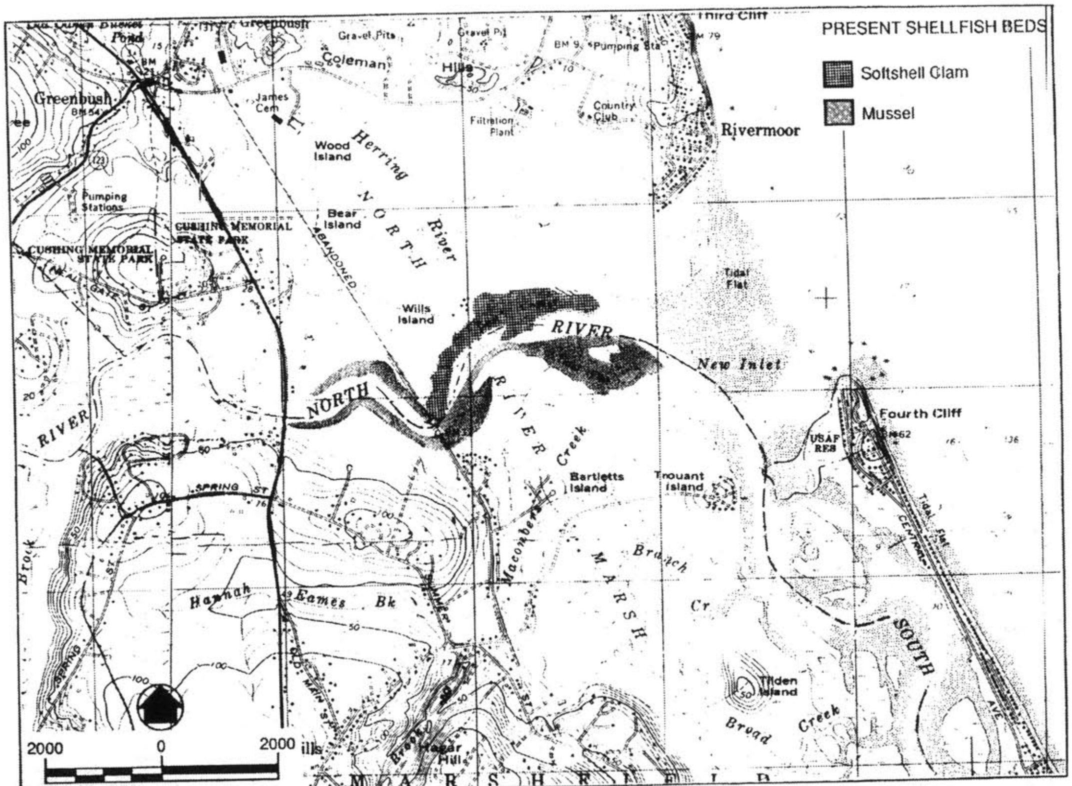



*Figure 5.1 Historical Shellfish Distribution in the North and South Rivers*




SOURCE: MDMF Shellfish Survey Data (1994)

*Figure 5.2 Present shellfish distribution in the North and South Rivers*

Furthermore, the North and South Rivers merit protection based on different regulations promulgated by federal and state agencies. Section 303 of Federal Water Pollution Control Act (FWPCA) requires states to classify the waters within their borders and develop water quality standards for each classification. Half of the North River and the entire length of South River are classified as Class SA waters. The rest of North River, from Indian Head to Third Herring Brook, is classified as Class SB waters (BSC, 1987). Class SA waters are the most protected classification possible under the Commonwealth of Massachusetts Department of Environmental Quality Engineering standards. As well, the North River is one of 48 rivers in Massachusetts to be declared a Scenic River under the Scenic and Recreational Rivers Act.

### 5.3 Functions of the Model

NSRWA can use the results from the fecal coliform model for the following purposes:

1. To understand the effect of complex hydrodynamic conditions on the water quality within the rivers
2. To evaluate the response of the North and South Rivers to point and non-point pollution sources
3. To establish a baseline to compare with future loading conditions
4. To make predictions on water quality of the rivers based on a specified loading
5. To serve as a preliminary water quality model that can be further improved in the future as more data are gathered
6. To help guide future fecal coliform monitoring and the collection of data for calibration of other water quality constituents

# 6. Current available fecal coliform data

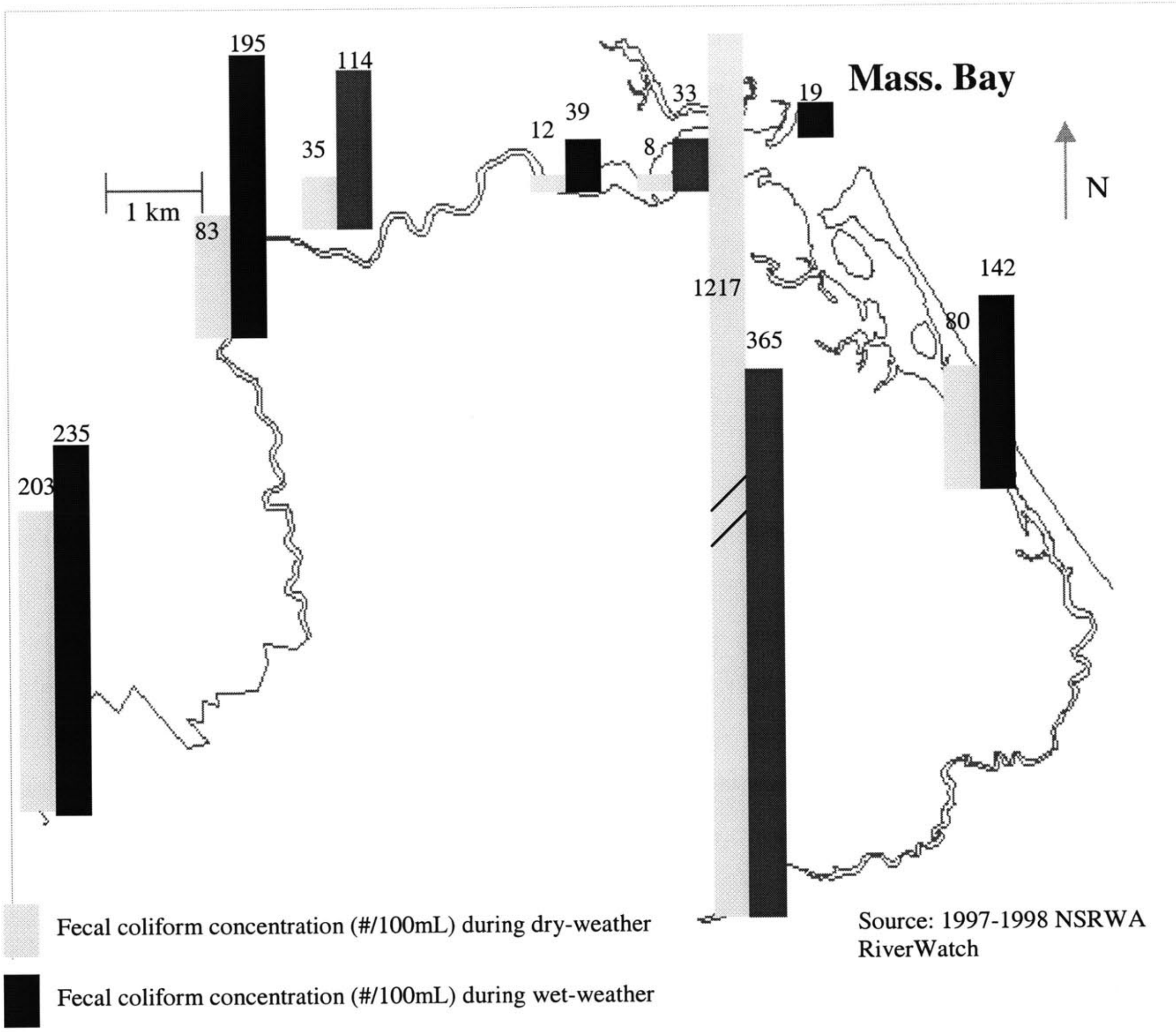
The existing fecal coliform data come from many different sources and were collected for various purposes. Unfortunately, none are very well suited for the purpose of water quality modeling. Currently, the most complete sets of fecal coliform data are from NSRWA's RiverWatch program (1997-1998), sources of the Division of Marine Fisheries (DMF) (1994), a report by the BSC group (1987) and two reports by the Baystate Environmental Consultants (BEC) (1990,1991).

## 6.1 NSRWA's Riverwatch program

The fecal coliform data set from NSRWA's RiverWatch program is the most complete. The Association is concerned about the overall health of the rivers and its impact on the residents. In their studies, volunteers obtained water samples at ten locations throughout the North and South Rivers. Fecal coliform testing was performed weekly in the months of July and August 1997 and 1998. Sampling occurred only in the warm season for several reasons. It is regarded as the most critical period of the year. First, the North and South Rivers receive an influx of seasonal residents and recreational boaters and experience the maximum negative water quality impact in the summer from recreational activities. Second, the summer has low freshwater inflow and discharge and would produce a minimum amount of dilution and mixing.

Figure 6.1 shows the distribution of fecal coliform concentration throughout the rivers during dry and wet-weather. These concentrations are the geometric means of all data at each location. Locations such as Willow Street Bridge in the South River and Washington Street Bridge in the North River have fecal coliform levels that are orders of magnitude higher than at other locations. The complete set of data is located in Appendix B.

*Figure 6.1 Distribution of fecal coliform concentration during dry and wet-weather flow*




## 6.2 Division of Marine Fisheries

The DMF collects samples to determine the state of the regional shellfish beds and to determine if the shellfish beds can be opened. Since the target level for shellfish harvesting is only 14/100mL, some samples with concentration exceeding 50/100mL are automatically discarded (Churchill, 1999). Therefore, the data may not be completely representative of the actual conditions in the field. However, the data are still valuable since experienced professionals collected them. Furthermore, information such as the number of waterfowl and boats were also collected. The complete set of fecal coliform data from the DMF is located in Appendix B.

### 6.3 The BSC Group Report

The data from the BSC group consist of nine months of bimonthly fecal coliform data (Appendix B). The purpose of this study was to examine the characteristics of the North and South Rivers and to identify possible pollution sources. Seasonal trends in fecal contamination in the North and South Rivers can be observed in Figures 6.2 and 6.3. The difference in bacteria concentration between flood tide and ebb tide is shown in Figure 6.4.

Fecal coliform levels peak at various locations in the North and South Rivers. Seasonally, fecal coliform levels generally peak during the summer season. As expected, most stations exhibit higher fecal coliform concentration during ebb tide than flood tide. This is because higher flows produce lower bacteria concentrations, as the additional water dilutes the bacteria.

Like fecal coliform (FC), the fecal streptococci (FS) bacteria group is indicative of organisms from the intestinal tract of humans and other warm-blooded animals. The ratio of FC/FS are frequently used to determine whether the sources of bacteria are from humans (FC/FS>4) or from warm-blooded animals (FC/FS<1) (Thomann and Mueller, 1987).

Fecal Streptocci bacteria were tested in the study performed by the BSC group. Of the 70 samples, only 3 have a FC/FS ratio of greater than 1 and none greater than 4. This suggests that the majority of bacteria originate from the intestinal tract of warm-blooded animals. This should be taken into consideration when applying the model.

In addition, the BSC group sampled several storm drains that are close to the rivers. These storm drains were tested for fecal coliform levels under both dry and wet-weather conditions. This data are used as loading input for the fecal coliform model (Chapter 9).

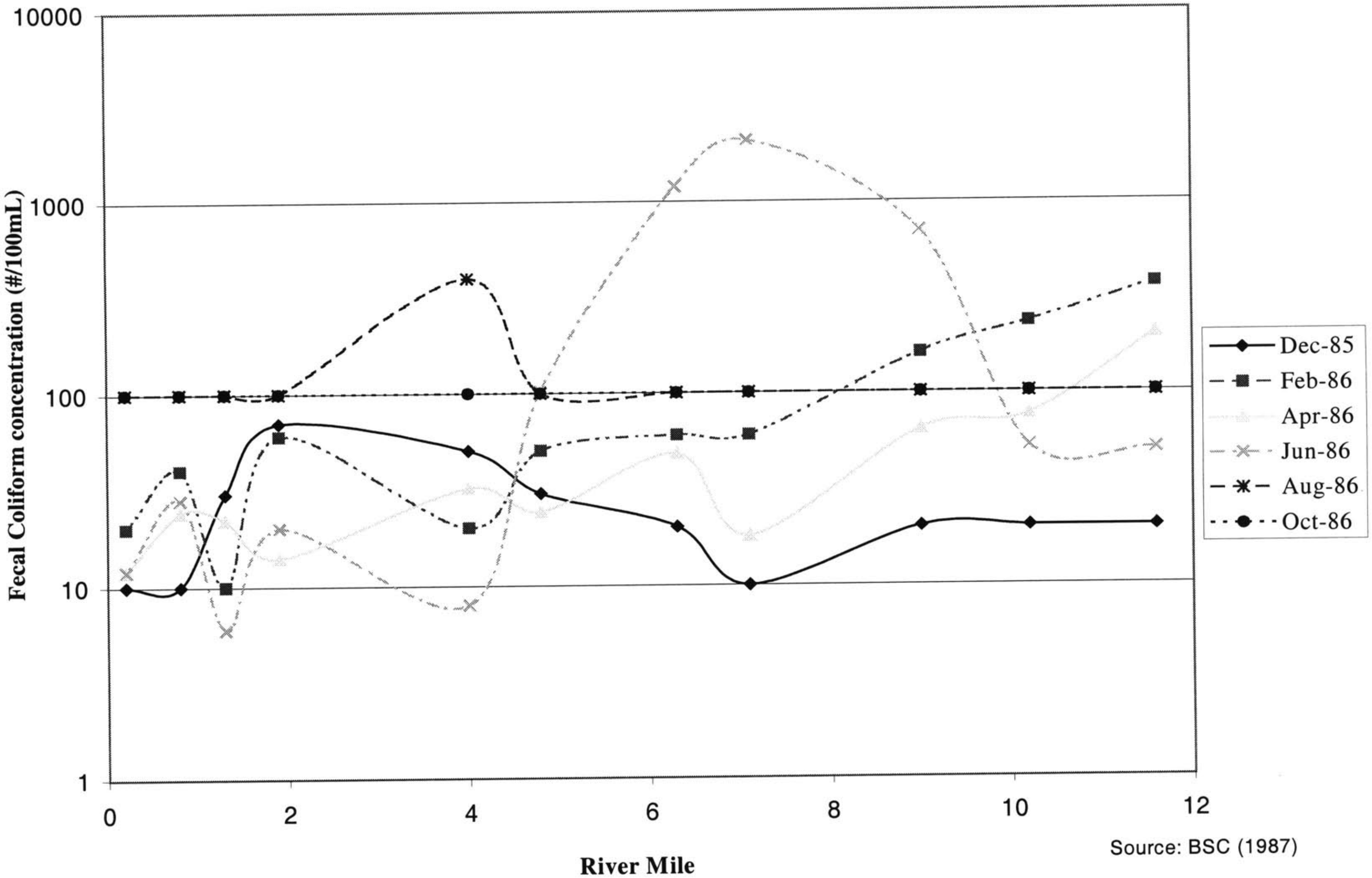
### 6.4 The Baystate Environmental Consultants (BEC) reports

The studies performed by BEC consist of fecal coliform data for North River and its tributaries (Appendix B). All flows and fecal coliform concentrations are given in three categories: low, typical, and high. The BEC report provides the most complete fecal coliform loading for various tributaries along the North River.

### 6.5 NSRWA's Storm water investigations relating to South River

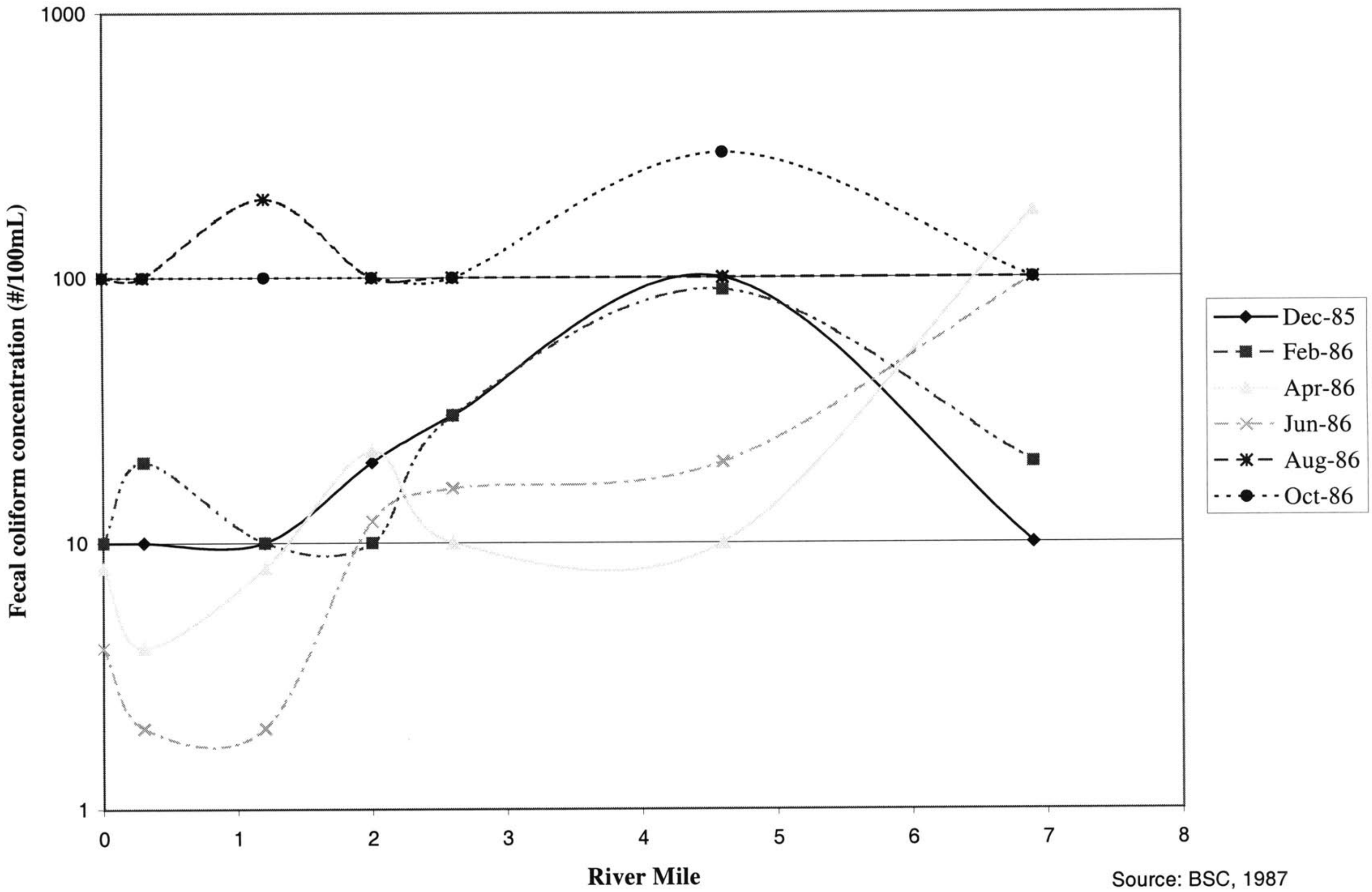
The objective of this report was to perform a preliminary investigation of storm water drainage systems discharging to the South River. NSRWA identified some storm drains that contaminate the South River significantly and located several storm drains with dry-weather flow. This data provided the basis for the development of the dry and wet-weather storm drain modeling scenarios discussed in Chapter 9.

*Figure 6.2 The effect of seasonal variations on fecal coliform concentration in the North River (Ebb Tide)*




Source: BSC (1987)

*Figure 6.3 The effect of seasonal variations on fecal coliform concentration in the South River (Ebb tide)*




Source: BSC, 1987

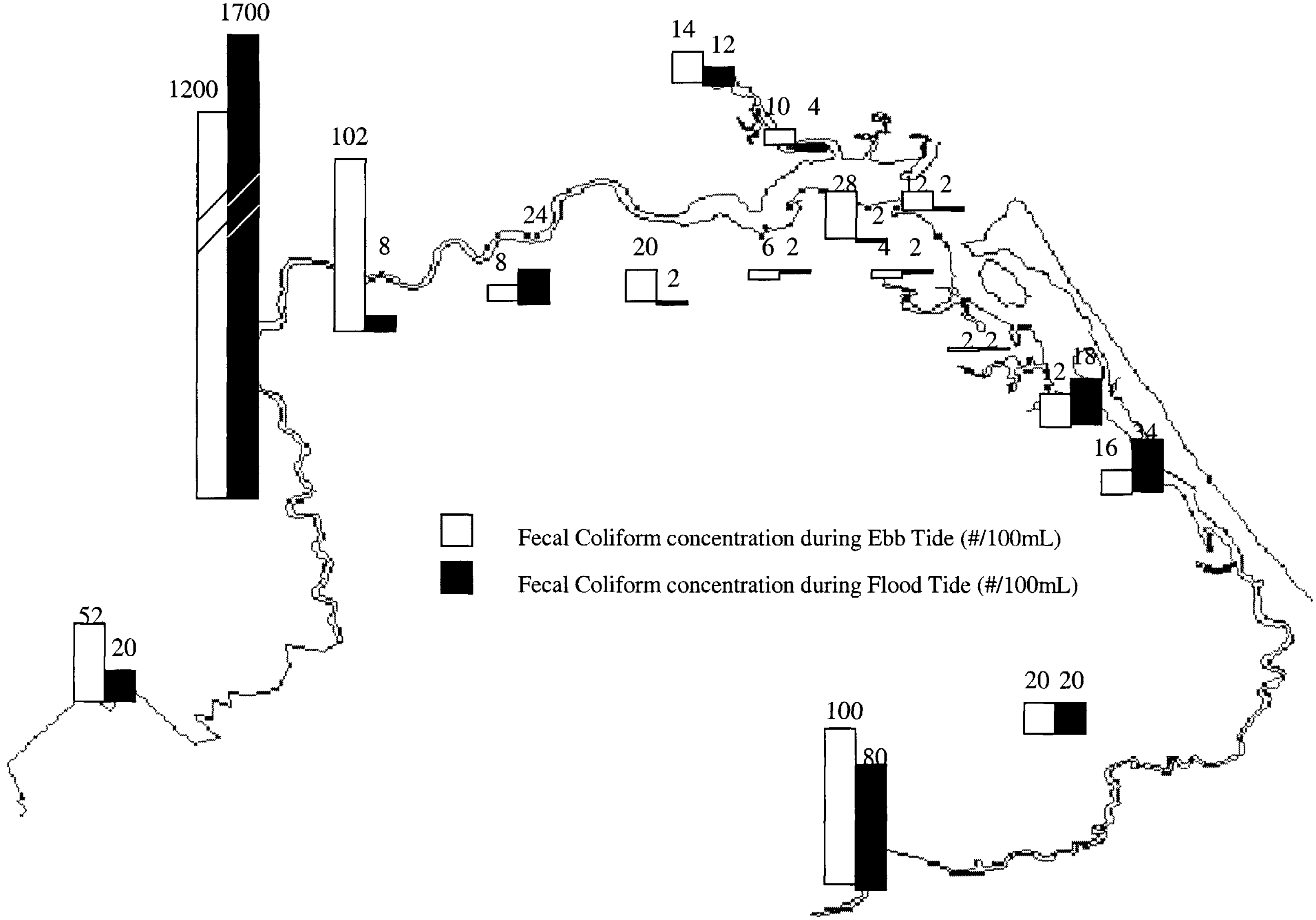



*Figure 6.4 Fecal coliform concentration during ebb and flood tide on June 18, 1986*

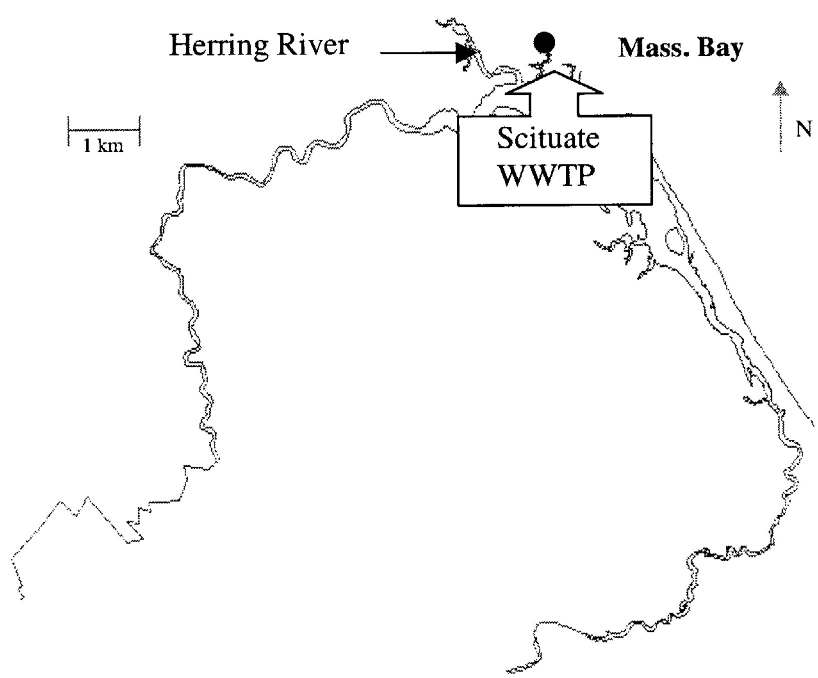
# 7. Fecal Coliform Sources and loadings

Each of the major fecal coliform sources within the watershed is examined and loadings into the rivers are estimated. These sources are contributed by animals or humans and can be divided into point and non-point sources.

## 7.1 Waste Water Treatment Plant

As most residences in the North and South Rivers watershed are equipped with private septic systems, there is only one wastewater treatment plant in the watershed. The Scituate wastewater treatment plant (WWTP) has only one discharge point and it discharges into a tidal ditch that flows into Herring River (Figure 7.1). The plant's average design flow is approximately 1.6 million gallons per day (MGD) and serves approximately 40% of the homes and businesses in Scituate.

*Figure 7.1 Location of Scituate Wastewater Treatment Plant*



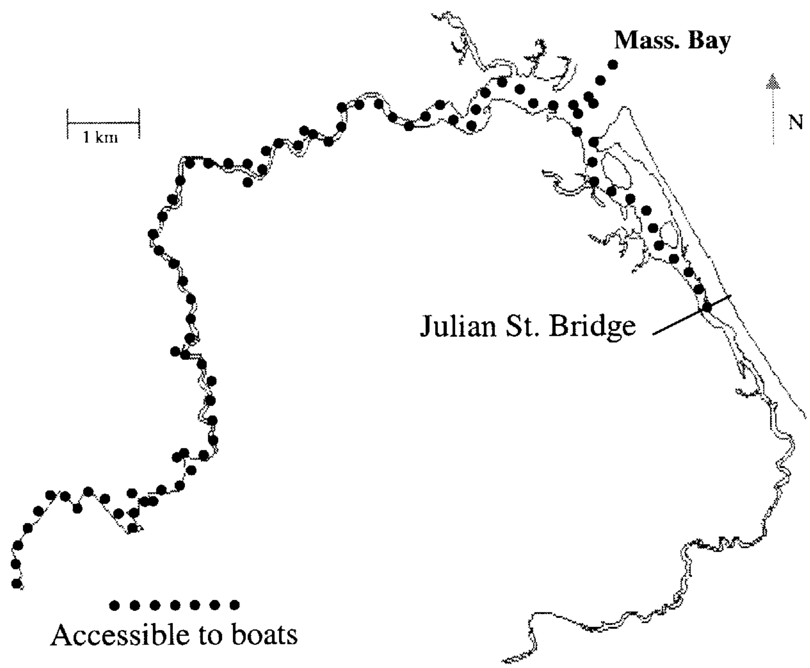
The waters affected by effluent discharge from Scituate WWTP are classified by the Department of Environmental Protection (DEP) as Class SA waters (Section 5.2). The limit for fecal coliform discharge is a geometric mean of 14/100mL, with no more than 10% of samples exceeding 43/100mL. As well, FWPCA of 1972 require a minimum of secondary treatment. Currently, the performance of Scituate WWTP exceeds the requirements for secondary treatment. However, the WWTP often exceeds the fecal coliform limit in the summer months (Metcalf and Eddy, 1995 ; EPA, 1999).

Various fecal coliform samples show high levels of contamination in the tidal ditch that receives effluent from WWTP (Metcalf and Eddy, 1995). Near the WWTP discharge point, the average fecal coliform concentration in the tidal ditch is approximately 177/100mL at high tide and 500/100mL at low tide. Where the tidal ditch meets Herring River, however, the fecal coliform concentration decreases to 30/100mL at high tide and only 60/100mL at high tide (Metcalf and Eddy, 1995). Overall, the impact of treated effluent from Scituate WWTP on the overall health of the rivers is small.

### 7.2 Boat Discharge

Boat discharge of raw or treated sewage has been long been suspected as a possible source of fecal coliform in the North and South Rivers (BSC, 1987). Boats can travel up the entire length of the North River, but they can only travel up to the Julian Street Bridge in the South River (Figure 7.2).

*Figure 7.2 Possible boat discharge zone*




An attempt is made to quantify the amount of fecal coliform loading by boat discharges. As of January 1, 1999, the number of registered boats in Massachusetts was 146,957 (DFWELE, 1999). It is assumed that 0.5% of boats in Massachusetts, or 735 boats in total, are located in the North and South Rivers watershed. In 1987, the BSC group estimated that marinas in the North and South Rivers provide slips and moorings to 502 boats. In addition to these, many of the homes along the rivers have private docks. Based on these numbers, an estimate of 735 boats in total is reasonable.

Of these 735 boats, it is assumed that only 15% are 22 feet or larger, the size that would be large enough for overnight cruising and likely to have an installed toilet on board (Dickinson, 1998). This assumption results in only 110 boats in the area that pose a threat to the water quality of the area. According to a 1992 U.S. Fish & Wildlife Service national survey on boats and marine sanitation device (MSD), only 7% of boats over 22 feet have a Type I or Type II treatment system. This reduces the number of boats that discharge directly into the rivers to eight. The discharge fecal coliform concentration of MSDs is less than 20/100mL (Dickinson, 1999). Boat loadings into the rivers are very small when compared to other sources. However, raw sewage in holding tanks may be discharged illegally. Unfortunately, without any information, it is difficult to speculate on the number of boats that discharge into the rivers illegally.

The cumulative negative impact of marinas on estuarine water quality are well-documented (McAllister *et al.*, 1996). There are at least seven marinas along the rivers, but only one with pump-out facility at James Landing Marina in the North River (DFWELE, 1997 ; Thatcher, 1999), with none on the South River (Churchill, 1994). The deterioration of water quality adjacent to the marinas indicates that in areas where boats congregate, boats contribute to fecal coliform loading. These findings indicate that more pump-out facilities should be built.

### 7.3 Dry-weather discharges from storm drains

Dry-weather discharges from storm drains are a major source of fecal coliform pollution. The source of this contamination may originate from illegal, or faulty connections in residences or businesses or groundwater infiltration. Illegal connections are defined as facilities that connect their septic sewers directly to a storm sewer. Groundwater infiltration is a result of leaky pipes. Dry-weather discharges contribute to a constant dry-weather load. The most seriously affected storm drains are near the Driftway along First Herring Brook, adjacent to Route 3A along the North River and near Marshfield Avenue along the South River (BSC, 1987).

Data for dry-weather storm drain flows are obtained from the BSC report, the BEC reports, and the South River storm water investigation report. Figure 7.3 shows the locations of all sampled dry-weather storm drains in the North and South Rivers.

*Figure 7.3 Location of all storm drains with dry-weather flow*

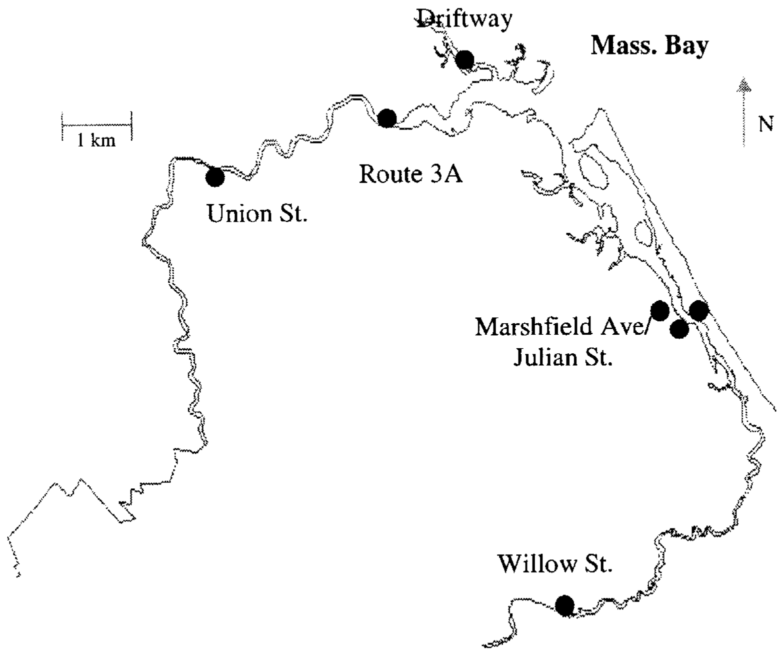
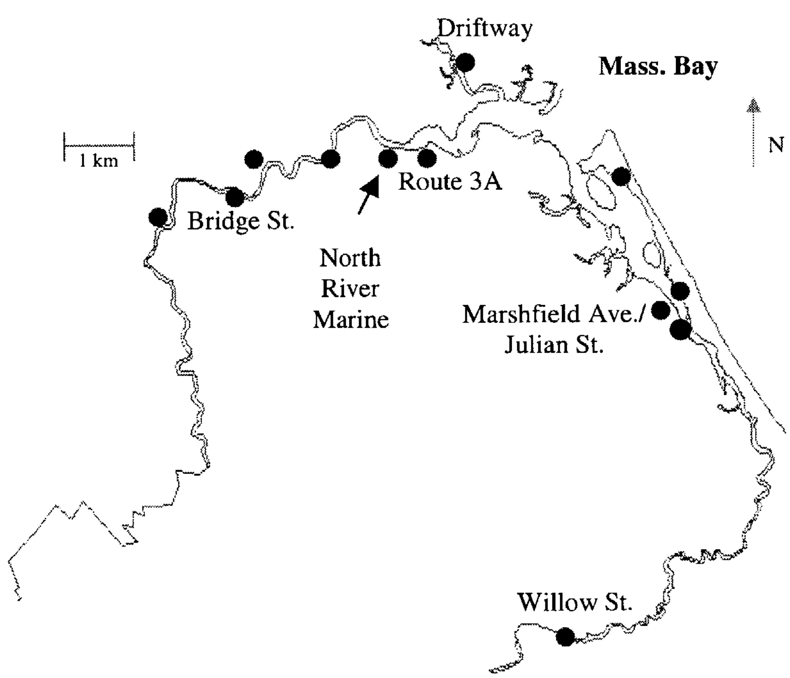



*Figure7.4 Location of all sampled storm drains (Dry and Wet-weather)*



### 7.4 Wet-weather discharges from storm drains

During wet-weather, fecal coliform loading into the rivers may originate from several sources. Although wet-weather fecal coliform loading includes overland flow and other sources, it is assumed that all wet-weather loading originates from storm drains.

Data collected in storm drains after storm events indicate the peak of contamination coincide with the initial discharge of stormwater (BSC, 1987). This initial discharge of contaminated storm water scours accumulated bacteria from various land surfaces. Although these storm events are short in duration, the amounts of bacterial load contributions are very high.

Although there are over 64 storm drains and catch basins adjacent to the South River (Churchill, 1994), only four have been tested with fecal coliform loading values. In addition, only storm drains with both flows and fecal coliform concentrations are included. As well, storm drains that do not discharge directly into the North and South Rivers are excluded. Figure 7.4 shows a map of all sampled storm drains in the North and South Rivers.

To determine how important wet-weather fecal coliform loading is relative to all other loadings, correlation between measured fecal coliform concentration and precipitation is investigated. Even though the North and South Rivers watershed is only 30 miles south of Boston, Boston's Logan Airport rainfall data cannot be used because of the large discrepancy found when the data is compared to local watershed precipitation data. This is especially true in the summer when storms are generally more localized.

Although the number of fecal coliform samplings with recorded precipitation is very small, examining this data would gain valuable insight to the overall fecal coliform loading distribution. The rainfall data shown below is the total amount of precipitation in 48 hours prior to sampling run (NSRWA, 1997, 1998). Rainfall data and bacteria measurements for each sampling day are plotted to determine how well they correlate (Figure 7.5).

Of the ten stations, only Julian Street Bridge and Willow Street Bridge stations are located on the South River. Although these two stations have very high overall concentrations, the rainfall-bacteria concentration correlation in these two stations are very low ($r^2$=0.0347, $r^2$=0.0351). The results suggest that wet-weather loading is not significant in these two locations and that other factors contribute to the high concentrations. From Figure 7.3, it can be seen that there are storm drains with dry-weather flow nearby. However, more investigations are still needed to determine the exact sources of bacterial contamination in these areas.

In the North River, most stations show good correlation between rainfall and fecal coliform concentrations with the exception of the Scituate outfall pipe, North River mouth, and Union Street Bridge. Given the complex hydrodynamics at the mouth of North and South Rivers, it is not surprising that the correlation coefficient at this location is low. The low correlation coefficient for the Scituate outfall pipe is also not surprising. The performance of the Scituate WWTP should not be significantly affected by the weather. At the Union St. Bridge, there is a storm drain with unusually high dry-weather flow rate containing high fecal coliform concentrations (BSC, 1987).

*Figure 7.5 Correlation plots between precipitation and fecal coliform concentrations*

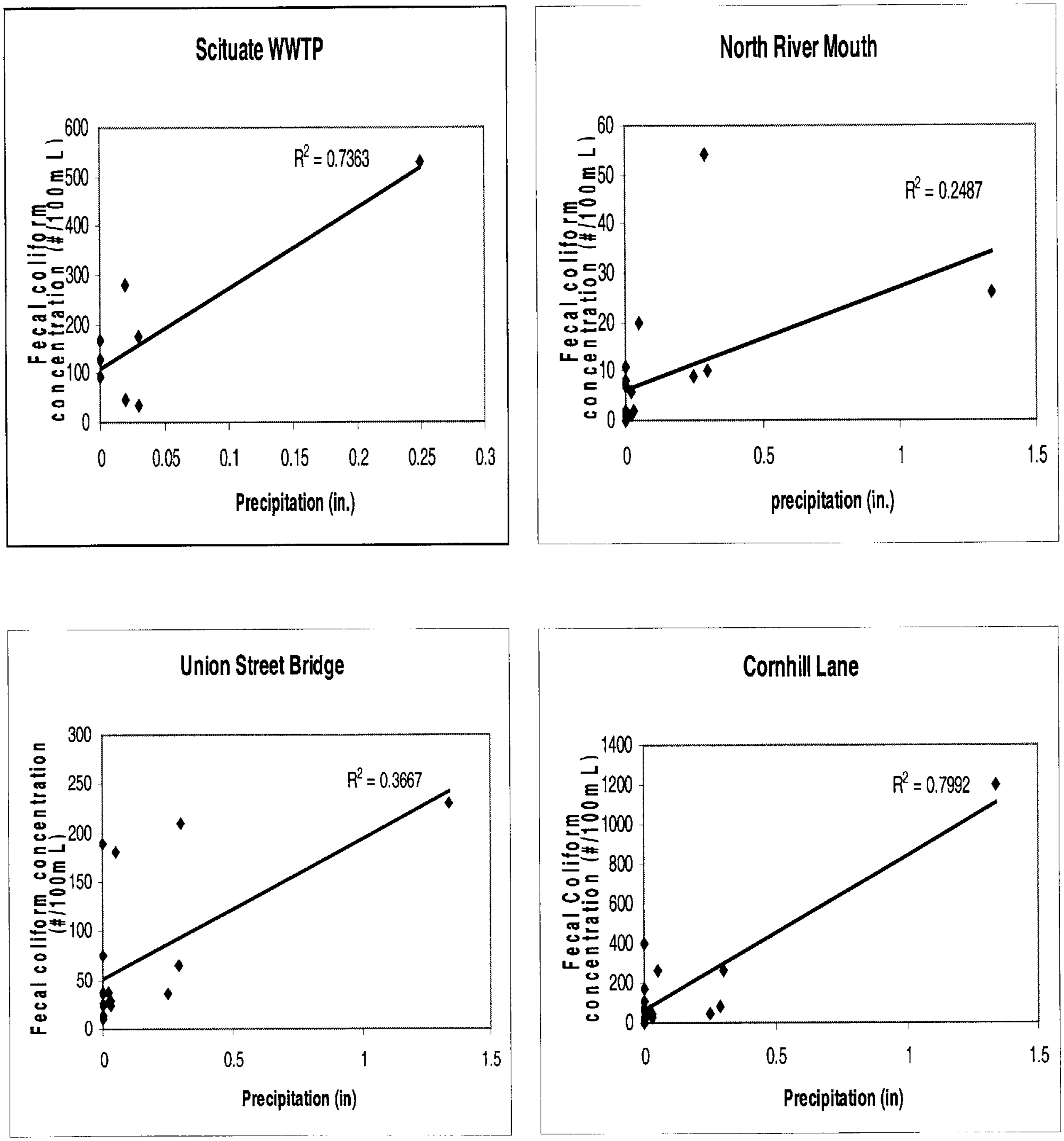
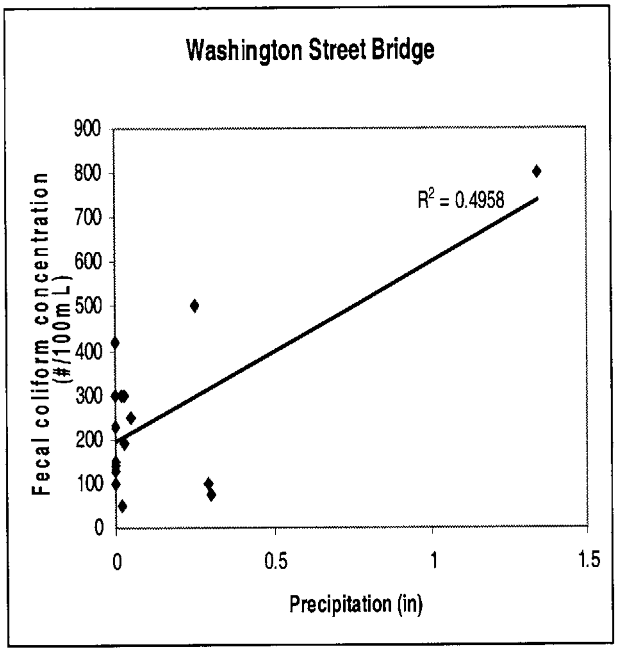
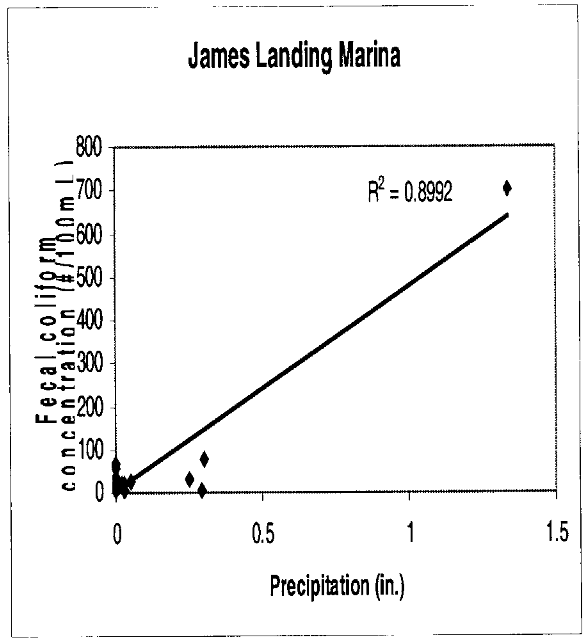
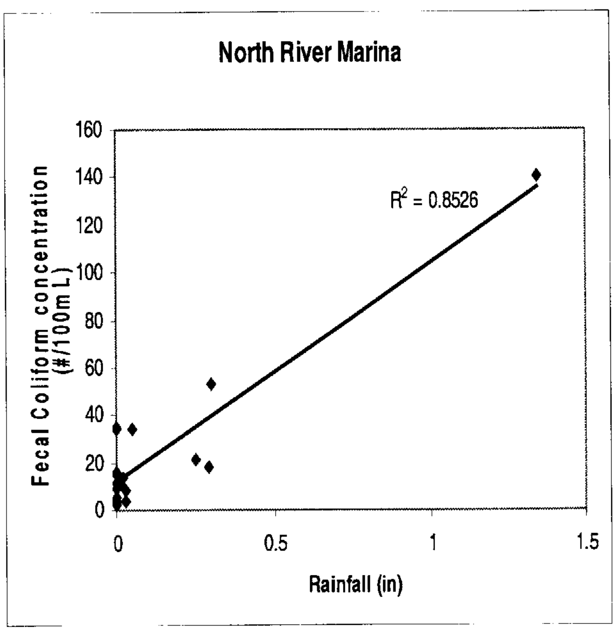


*Figure 7.5 Continued*



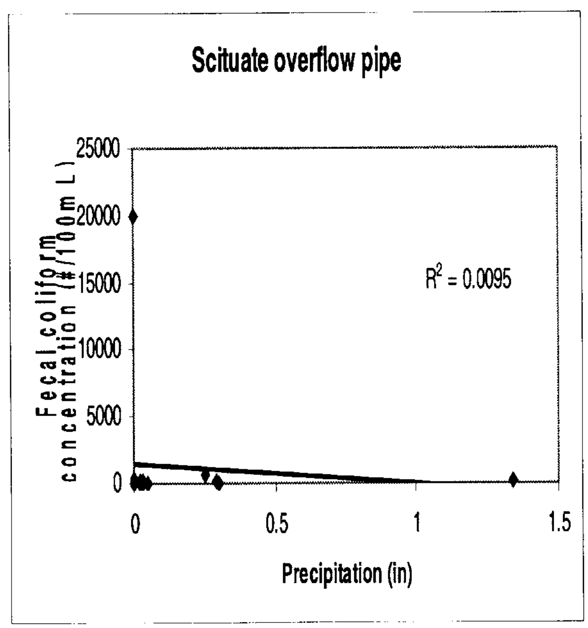
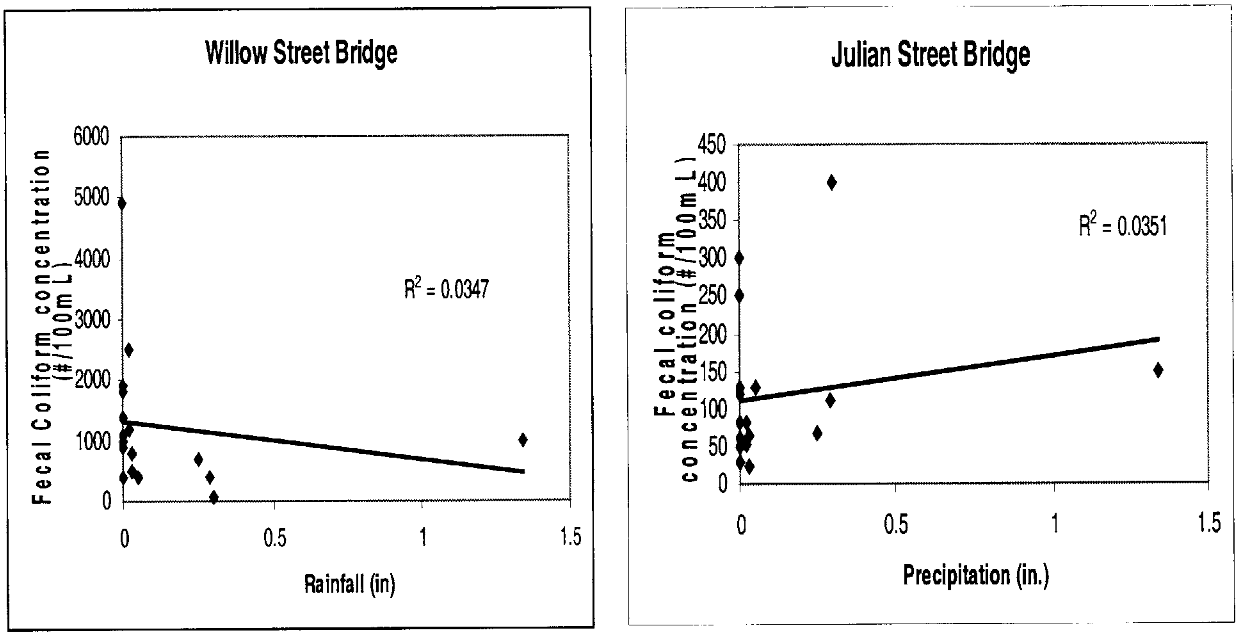



*Figure 7.5 Continued*

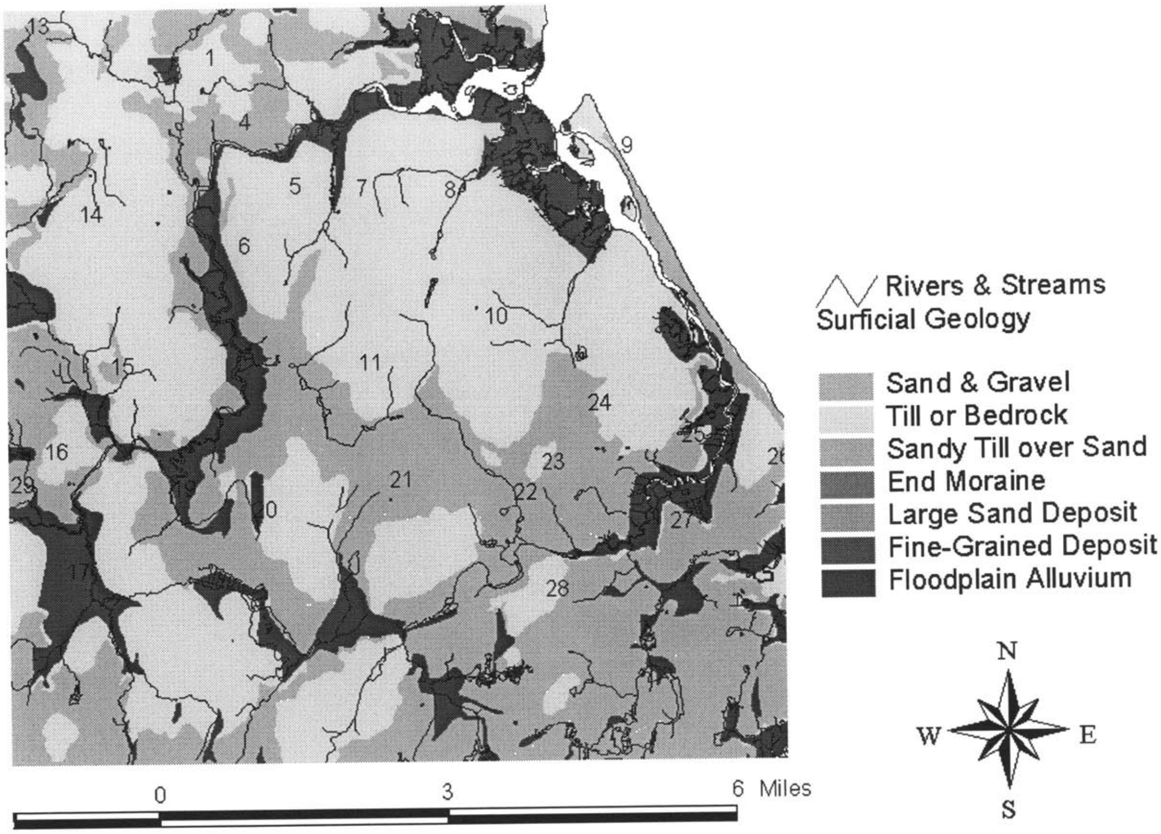



## 7.5 On-lot disposal system

Wastewater disposed of through on-lot disposal system such as cesspools or septic tanks percolates to groundwater and eventually reaches the rivers. Increase in fecal coliform load in rivers has been found to correlate well with increase in housing density (Morrill and Toler, 1973). As well, increase in fecal coliform is closely associated with the rise of the water table following major rainfall periods (Hagedorn *et al.*, 1978).

.

Geology in the watershed is characterized by granite bedrock overlaid with 3 to 25 meters of glacial outwash and gravel or glacial till (BSC, 1987). The surficial geology in the area is shown in Figure 7.6.




Source: MassGIS (1995)

*Figure 7.6 Surficial Geology*

With the exception of 40% of homes and businesses in Scituate, homes and businesses in Scituate and all other municipalities in the watershed rely on cesspools or septic tank systems for on-lot wastewater treatment and disposal (Figure 7.7). According to the 1995 National Shellfish Register, the National Oceanic and Atmospheric Administration (NOAA) believes that individual wastewater treatment systems such as septic tanks have the highest level of impact on shellfish harvesting in the South River.

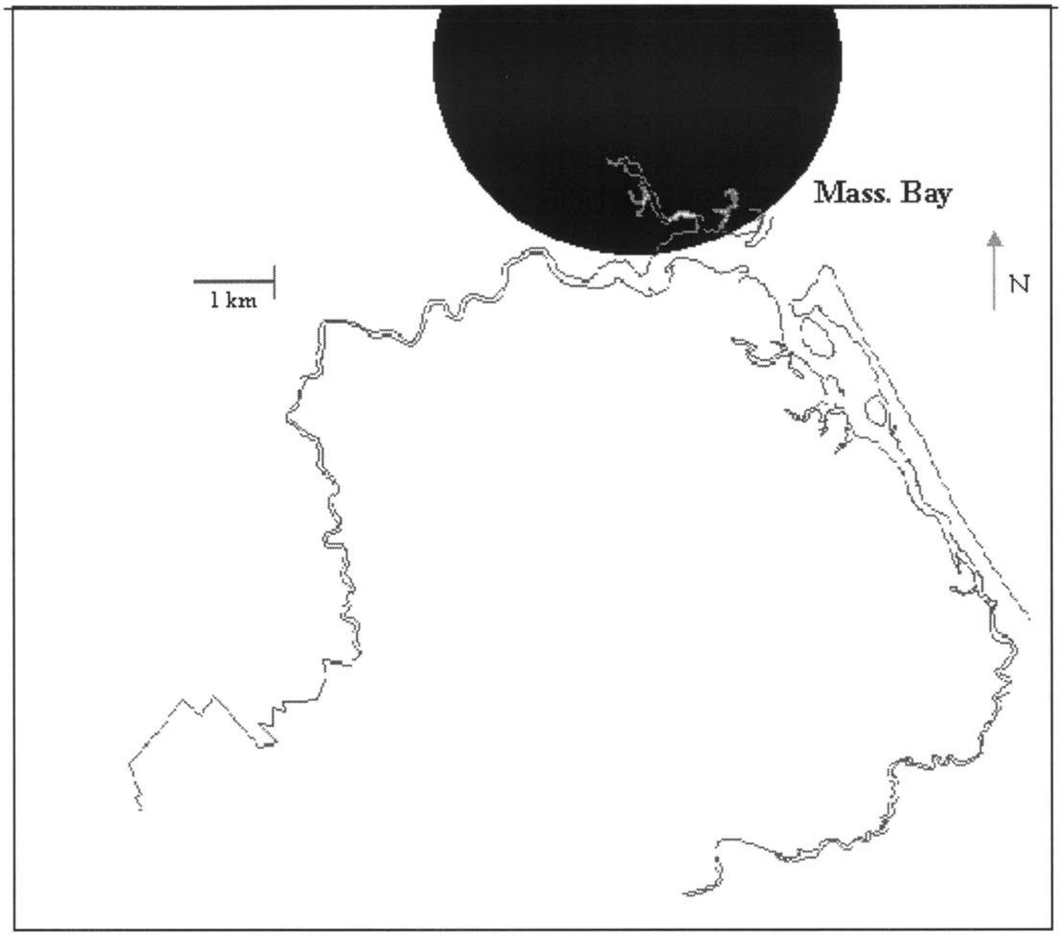



*Figure 7.7 Areas served by Scituate Wastewater Treatment Plant*

Although all new construction of septic tanks must meet regulations promulgated by Title 5 (1994) of the Environmental Code of Commonwealth of Massachusetts (310 CMR 15.00), many of the existing disposal systems are faulty. These systems fail because they are either too old, improperly designed, reside in poor soils, or lack of proper maintenance (Metcalf and Eddy, 1995).

Failed septic systems can affect the quality of both surface water and groundwater. The two methods by which on-lot disposal systems can contaminate the rivers are overflowing tanks due to transmission failures and groundwater contamination due to treatment failures.

In the preliminary shoreline survey report of the South River, none of the 203 household sewage disposal systems exhibited visible signs of failure (Churchill, 1994). However, one should be cautious about assuming these systems are safe without further testing. In particular, many of the disposal systems are very close to the mean high water mark.

A number of investigators (Gerba *et al.,* 1975 ; Viraraghavan, 1978) have found that coliform bacteria in effluent move only a few meters in soil while other investigators (Reneau *et al.,* 1975 ; Hagedorn *et al.,* 1978 ; Chen, 1988) found report long-distance travel. To determine the effects of on-lot disposal systems on the water quality of North and South Rivers, field tests must be performed.

### 7.6 Waterfowl droppings

Birds have been found to have a significant effect on river fecal coliform levels (Palmer, 1982). The amount of waterfowl fecal coliform loading in the North and South Rivers is estimated based on a study performed by Weiskel *et al.* (1996). Weiskel *et al.* estimated the number of waterfowl at Buttermilk Bay in Cape Cod, Massachusetts. To predict the number of waterfowl in North and South Rivers, a factor based on areas of the two regions is multiplied to the collected data at Buttermilk Bay.

The watershed area in Buttermilk Bay is 2.14 $km^2$. To calculate the area for North and South Rivers, the lengths of the Rivers are multiplied by an assumed width. The total lengths of North and South Rivers are 12.7 miles and 6.0 miles respectively. It is assumed that waterfowl within 1000 feet of the Rivers contribute to fecal coliform loading. The calculated discharge area for the rivers is approximately 10 $km^2$. The affected areas in North and South Rivers are approximately five times larger than at

Buttermilk Bay. This factor of five is then applied to Weiskel's data and the following results are obtained (Figure 7.8)

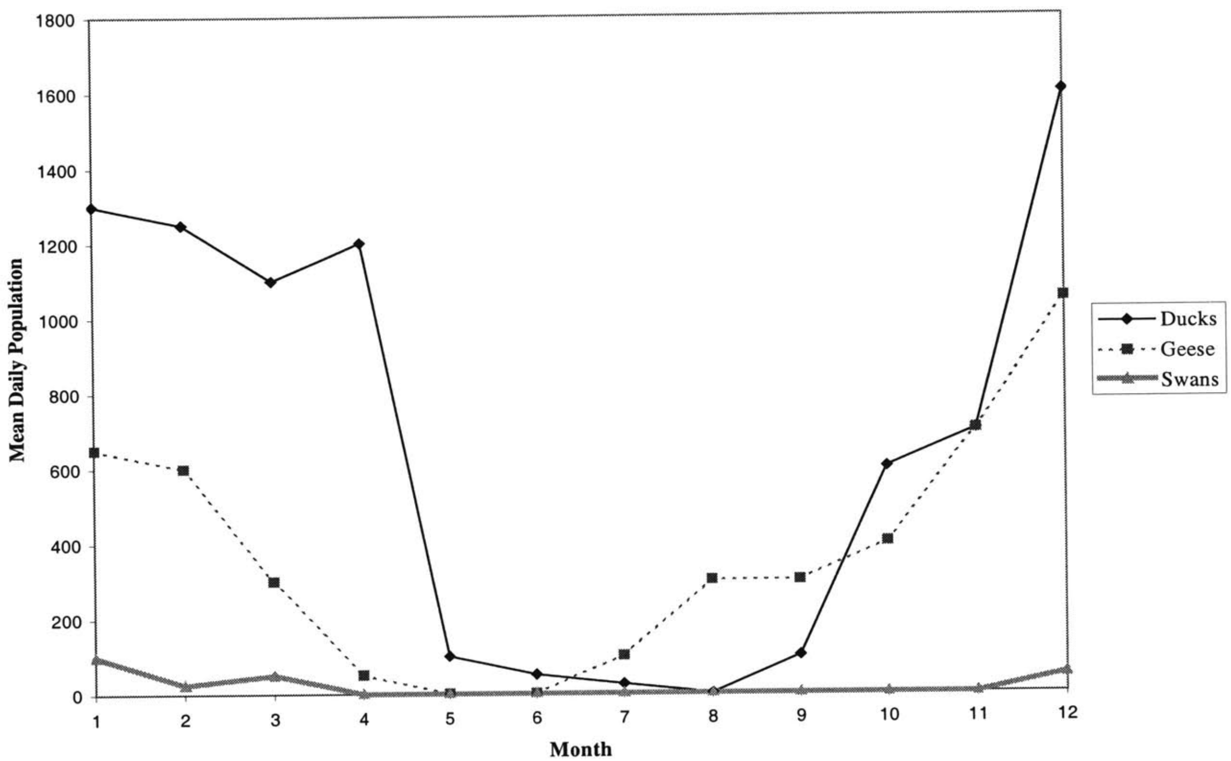



*Figure 7.8 Estimated waterfowl populations in the North and South Rivers*

The fecal coliform input is estimated from population counts of each avian type and published values of fecal matter production rates. Typical fecal coliform discharge values are $10^9$, $10^7$, and $10^9$ for ducks, geese, and swans, respectively (Weiskel, 1996). The total loading is then reduced by one-third as the waterfowl on the coastal embayments of the region spend one-third of their time feeding away from the waters (Buchsbaum and Valiela, 1987). Resulting loadings are shown in Figure 7.9.

While direct waterfowl inputs are a large source of fecal coliform to the North and South Rivers, there may not be a direct relationship between this input and fecal coliform levels in the rivers. The highest fecal coliform concentrations are generally in the summer months whereas waterfowl numbers and loadings are highest in the winter months.

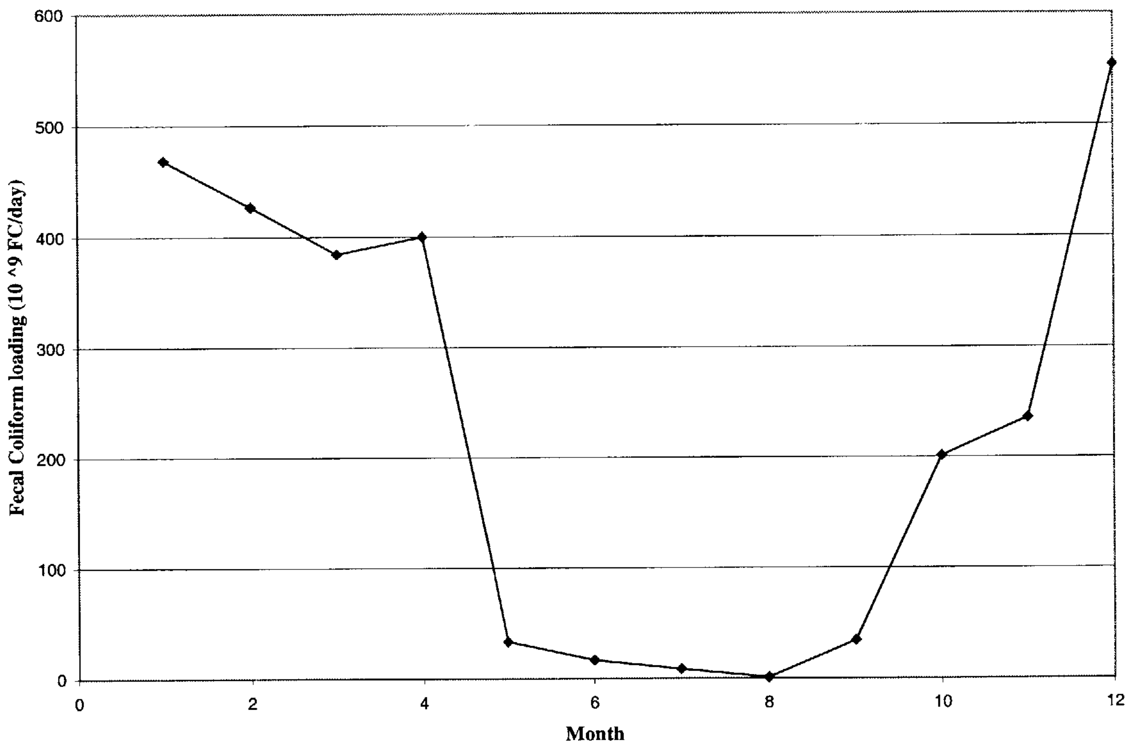



*Figure 7.9 Estimated total fecal coliform loading by waterfowl*

### 7.7 Tributary Loading

Tributary bacterial loads are calculated based on estimated tributary flows and fecal coliform measurements. Estimated flows and bacteria measurements are obtained from the BEC reports (1990, 1991).

### 7.8 Other Sources

There are various other sources of fecal coliform that are not taken into consideration due to lack of available data. Some of them include overland runoff (Weiskel *et al.,* 1996), decomposing organic matter from wetland areas (BSC, 1987), and resuspension of contaminated sediments in the rivers (Palmer, 1988).

# 8. Fecal coliform decay

## 8.1 Governing equation

The rate of fecal coliform bacteria disappearance is based on first order decay. In RMA-11, the rate of decay is modeled using three loss parameters: settling, decay in darkness, and light sensitive decay (King, 1997). All these parameters are temperature adjusted as discussed in Chapter 2.1.3.

The loss rate for fecal coliform bacteria ($G_c$) can be represented as

$$G_c = -(K_{c1} + K_{c2} + K_{c3}/d)\, C_c \qquad (8.1)$$

where

| | | |
|---|---|---|
| $C_C$ | = | the concentration of coliform, (# of fecal coliforms/100mL) |
| $K_{c1}$ | = | coliform die off rate in darkness - temperature adjusted (1/hr) |
| $K_{c2}$ | = | coliform die off rate due to light - temperature adjusted (1/hr) |
| $K_{c3}$ | = | coliform settling rate - temperature adjusted (m/hr). |
| d | = | depth of water body |

A more detailed discussion on each of the three parameters can be found in Appendix C.

## 8.2 Decay coefficients used in previous studies of the North and South Rivers

None of the three previous studies that dealt with fecal coliform decay coefficients determined these coefficients experimentally. Each study obtained its value by using typical or default values. Metcalf and Eddy (1995) used the default value of 0.5/day as given by the WQONN model. The BSC Group (1987) chose a die-off rate of 1.0/day, as it is believed to be most commonly used by other investigators. Investigators from the BEC Group (1990, 1991) used the same die-off rate of 1.0/day and same reasoning.

### 8.3 Decay coefficients in existing literature

Large range of reported decay rates exist for fecal coliform. Typical die-off coefficient for fecal coliform in seawater is 1.4/day at 20°C, but can range up to 6.1/day in sunlight (Mancini, 1978);(Thomann and Mueller, 1987).

### 8.4 Values used in RMA-11

Although no single die-off rate describes coliform mortality, we have decided to use a uniform coliform decay rate of approximately 1/day. This task is difficult in RMA for several reasons. RMA-11 does not allow for a single decay value. The input values RMA-11 requires are settling rate for coliform, 90% decay time for darkness, light coefficient, and light extinction. All these values require experimental data that are not currently available.

To obtain a decay value of 1/day, the approach chosen is to enter a settling rate value. The settling rate is divided by depth to obtain $K_{c3}$ from Equation 8.1. All other parameters are assumed to be zero. The depth of the rivers is highly variable depending on the time of tide and location (Tana, 1999). The average depth is assumed to be 1.5 meters. The input value for settling rate is entered to be 1.5m/day to obtain an approximate value of 1/day.

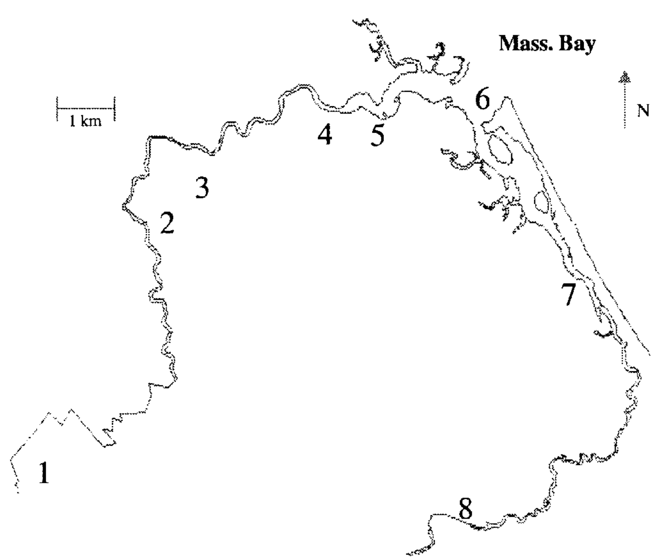
Although the temperature for all trials remains at 20°C, for completeness, the temperature coefficient for coliform decay and coliform settling used is 1.047 (Brown and Barnwell, 1987).

# 9. Fecal Coliform modeling scenarios

A main objective of this study is to determine the impact of various pollution sources on the North and South Rivers, which would serve as a guideline for future management plans to mitigate these sources. This chapter examines the effects of repairing the existing storm drain system and thereby decreasing the amount of fecal coliform loading into both rivers.

Of all the potential fecal coliform sources discussed in Chapter 7, only four will be simulated in this chapter. As mentioned previously, although boat discharge and on-lot disposal systems may contribute greatly to the high fecal coliform concentration, the complete lack of data does not allow for any meaningful examinations of these sources. We developed four different fecal loading scenarios: (1) Tributaries only, (2) Waterfowl loading, (3) Dry-weather storm drain loading, and (4) Wet-weather storm drain loading. For simplicity, all scenarios operate at 20°C and are all in the month of July. The results from the model will be compared to actual data from the NSRWA's RiverWatch program. Figure 9.1 is a map of all station locations.

*Figure 9.1 Location of NSRWA Riverwatch stations*




1. Washington St. Bridge
2. Cornhill Lane
3. Union St. Bridge
4. North River Marine
5. Damon's Point
6. North River Mouth
7. Julian St. Bridge
8. Willow St. Bridge

### 9.1 Tributary loading only

All known tributary flows and fecal coliform concentrations are input into the model. The tributary loadings are input as boundary conditions with only specified fecal coliform concentrations since values of flow are inputs in RMA-10. Wherever possible, the mean fecal coliform concentrations are selected. The tributary locations are shown in Figure 9.2.

As shown in Table 9.1, tributary loadings contribute a small amount of bacteria to the North and South Rivers.

*Table 9.1 Tributary fecal coliform concentrations*

| Tributary | BC | FC (#/100mL) | Source |
|---|---|---|---|
| Indian Head | 1 | 33 | BEC |
| South River Schools | 3 | 276 | SR SWI |
| Herring River | 4 | 20 | M&E |
| Second Herring Brook | 5 | 235 | BEC |
| Third Herring Brook | 6 | 84 | BEC |
| Herring Brook | 7 | 36 | BEC |
| Macombers Creek | 8 | 1.3 | SR SWI |
| Cove Brook | 10 | 76 | BEC |
| Stony Brook | 11 | 49 | BEC |
| Dwelleys Creek | 12 | 53 | BEC |
| Broad Creek | 14 | 14 | SR SWI |

Note: BEC (Baystate Environmental Consultants); M&E (Metcalf and Eddy); SR SWI (South River Storm water investigation); BC (Boundary condition line in RMA-11)

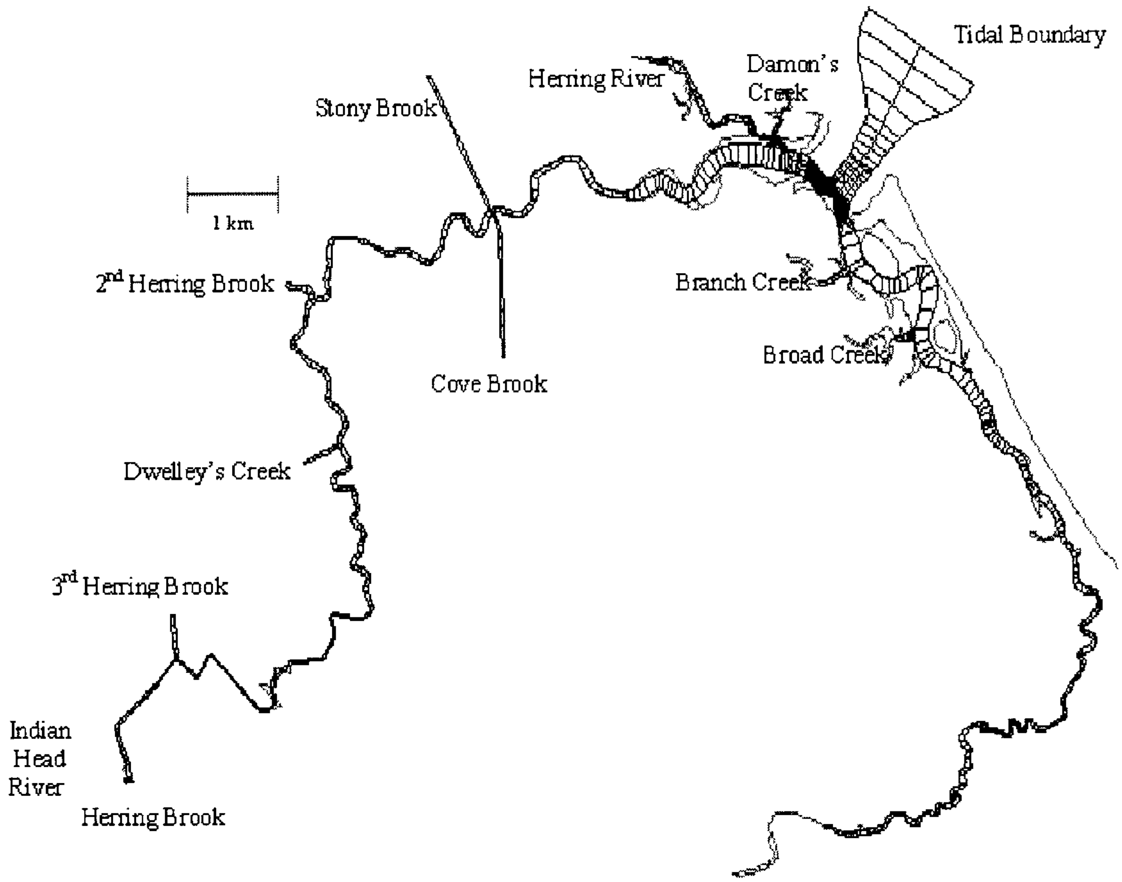



*Figure 9.2 Tide and Inflow Boundary location*

Figure 9.3 is a display of the results from the simulation. These results are from low tide to represent the worst water quality. With the exception of Washington Street Bridge and Union Street Bridge, tributary loadings do not have a large effect on the overall health of the North and South Rivers. Washington Street Bridge station is a short distance away from Indian Head River and Union Street Bridge is close to the Second Herring Brook.

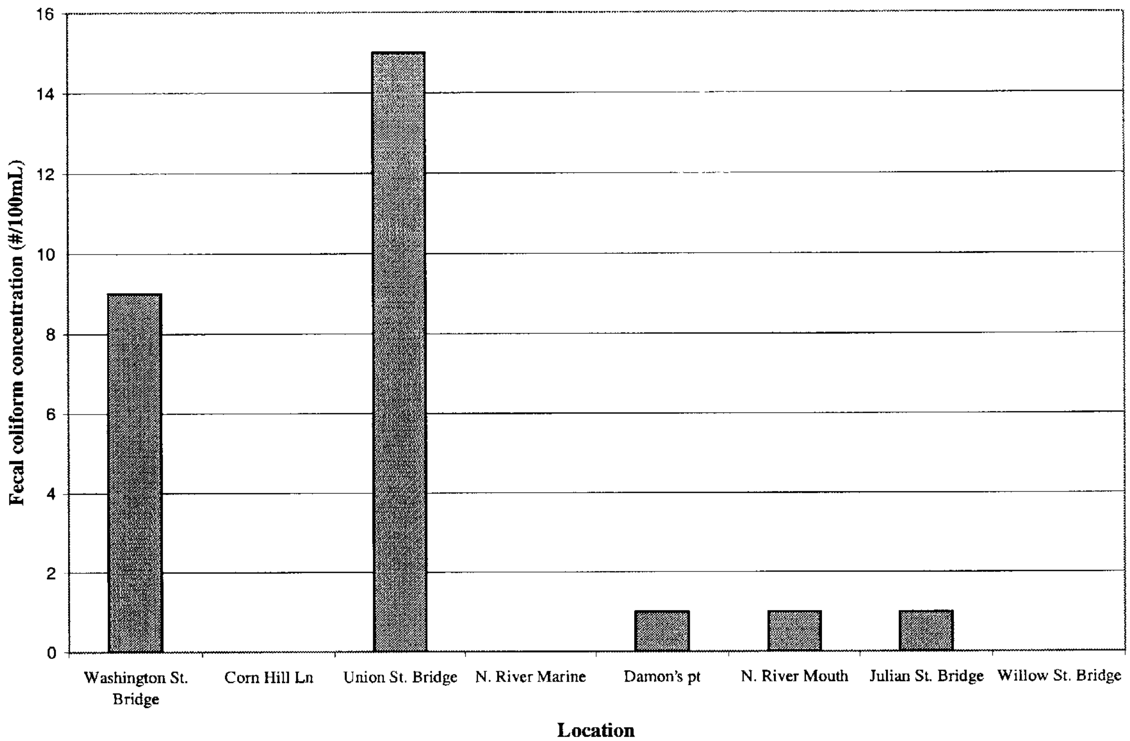



*Figure 9.3 Model simulation with tributary loading only*

## 9.2 Waterfowl loading

From the estimated total number of waterfowl and total waterfowl fecal coliform loading in Figures 7.8 and 7.9, there are an average of 25 ducks and 100 geese per day in July with a mean fecal coliform (FC) loading per day of $9.0x10^9$ FC/day. As discussed in Chapter 7.6, direct waterfowl inputs are limited to their effects on the overall bacterial concentration in the rivers. Three trials are simulated with (1) total predicted loading (100%), (2) 5% of total predicted loading at $4.5x10^8$ FC/day, and (3) 1% of total at $9.0x10^7$ FC/day. It was assumed that the birds are only active between 7 am and 7 p.m. and that the amount of fecal coliform loading is evenly distributed through their active hours. Furthermore, the waterfowl are assumed to be evenly distributed throughout the length of both rivers. The time step for this simulation is 0.5 hours and each waterfowl is represented as a point source. The results of the simulations are shown in Figure 9.4.

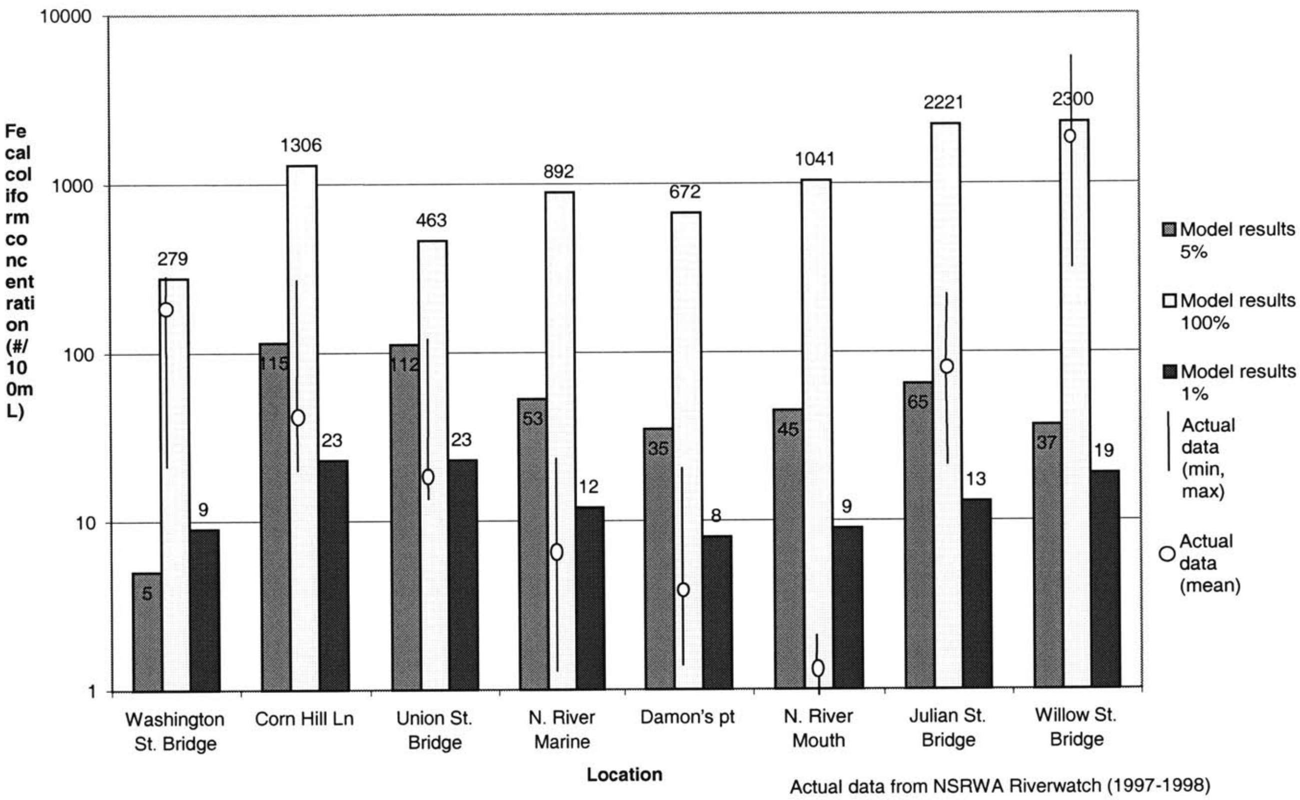



*Figure 9.4 Model simulated results from waterfowl loadings and tributary inputs*

The simulated model clearly shows that the predicted FC loading from waterfowl are overestimated. At 1% of the predicted loading, the simulated results are similar to actual data. This may be due to several factors. The natural patterns of the waterfowl are not taken into consideration in the model assumptions. The model assumes equally distributed waterfowl along the rivers and that they stay stationary. In reality, waterfowl have preferred areas along sections of the rivers, especially near the marshes. As well, waterfowl are not stationary animals. They naturally move around to various locations inside and outside the watershed. Furthermore, deposited fecal pellets tend to remain intact, which limit bacterial dispersal prior to die-off (Weiskel *et al.*, 1996). Simulating waterfowl is a difficult task without further understanding of their behaviors and patterns.

## 9.3 Dry-weather storm drain loading

Several reports identified a total of 7 storm drains in the North and South Rivers that discharge during dry-weather periods (Chapter 7.3). Table 9.2 shows the input values for fecal coliform loading from these drains.

*Table 9.2 Dry-weather fecal coliform input values*

| Storm drains | Flow (ml/sec) | FC (#/100mL) | Loading (#/sec) | Source |
|---|---|---|---|---|
| Union Street | 2800 | 31 | 878 | BEC (1991) |
| Marshfield Ave. | 0.083 | 200 | 1 | BSC (1987) |
| Landing (near 3A) | 30 | 100 | 30 | BSC (1987) |
| River Circle | 300 | 100 | 300 | BSC (1987) |
| Bridgwaye Inn | 157.5 | 16 | 25 | SR SWI (1993) |
| Sea Street | 1575 | 11 | 173 | SR SWI (1993) |
| Willow Street | 1890 | 120 | 2268 | SR SWI (1993) |

Note: BEC (Baystate Environmental Consultants); BSC (The BSC Group); SR SWI (South River Storm water investigations)

It is recognized that part of dry-weather storm drain flows may originate from illegal connections, thus causing the real loadings of fecal coliform to fluctuate depending on the amount of water usage and, hence, the time of day. However, since this information is unavailable, it is assumed that dry-weather storm drain flows are continuous at the same rate for all times. Each storm drain is treated as a continuous point source throughout the rivers.

Figure 9.4 shows the result of this simulation. The NSRWA Riverwatch data shown only contain dry-weather samples. The simulation matches well with actual data except for three locations: Washington Street Bridge, Cornhill Lane, and Julian Street Bridge. There is a lack of fecal coliform studies and data collections in the upstream portion of the North River. In our simulation, the only fecal coliform source near Washington Street Bridge is from the Indian Head River. There may be storm drains and other sources in this area that have yet been investigated. The same holds true at Corn Hill

Lane. Since investigators are most concerned about areas near shellfish beds, fecal coliform sources at this station may not have been studied thoroughly. Discrepancies at the Julian Street Bridge, however, may be the result of several different reasons. First, there are many storm drains near Julian Street Bridge that are not modeled because storm drain flow data are not available. Second, there is a large boat yard at Julian Street Bridge that may contribute bacteria into the South River. Lastly, Julian Street Bridge is near Humarock, where high density of houses with septic systems is located.

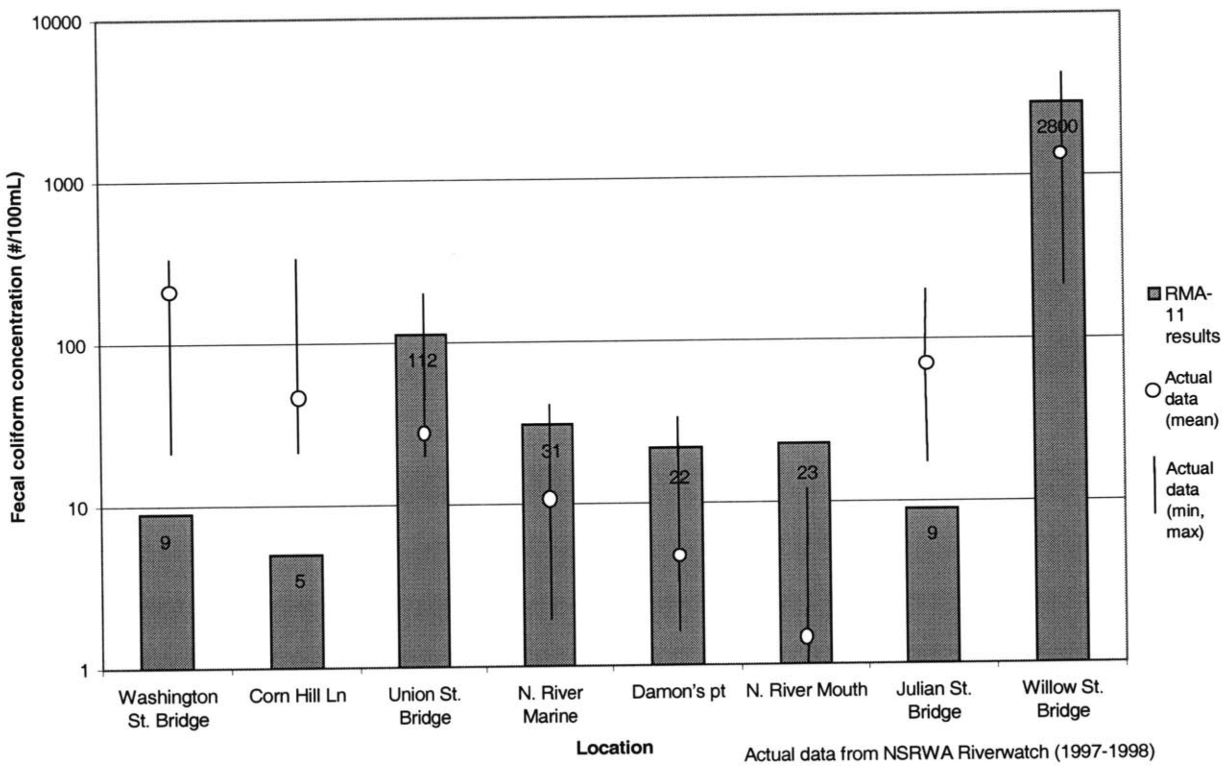



*Figure 9.5 Model results from dry-weather storm drains and tributary inputs*

Figures 9.6 and 9.7 are combined plots of dry-weather storm drains, waterfowl inputs at 1% of estimated value and tributary inputs at low tide and high tide, respectively. As expected, contaminate concentrations at high tide is considerably lower than at low tide due to the effect of seawater dilution.

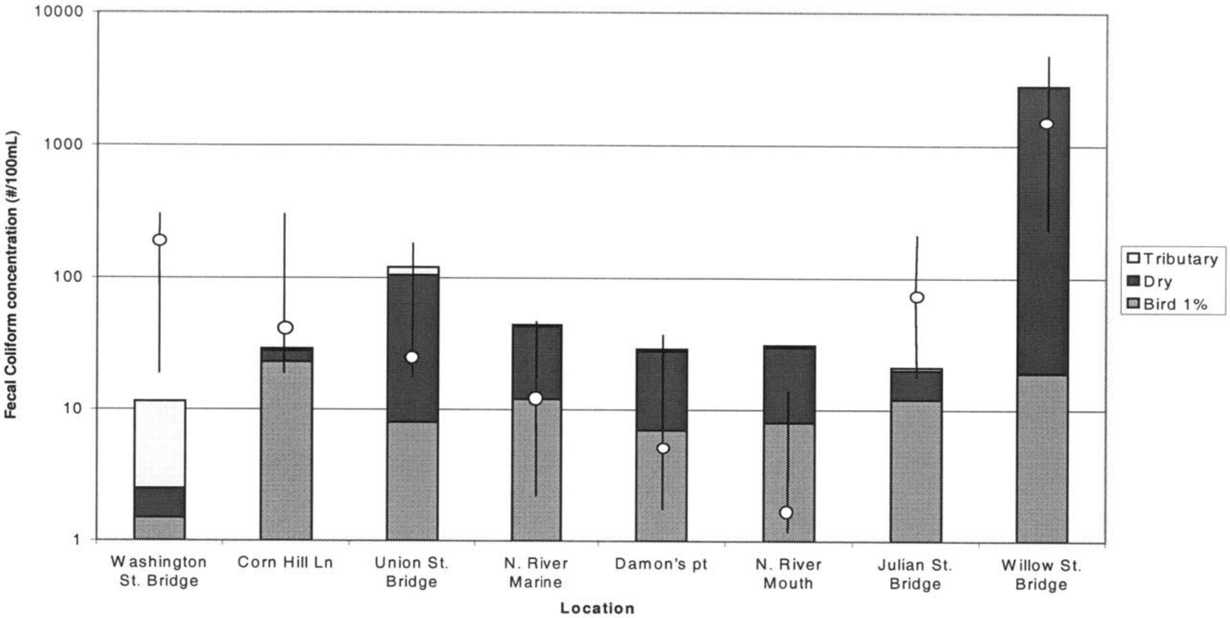



*Figure 9.6 Summary plot of receiving water fecal coliform concentrations at low tide due to dry-weather sources*

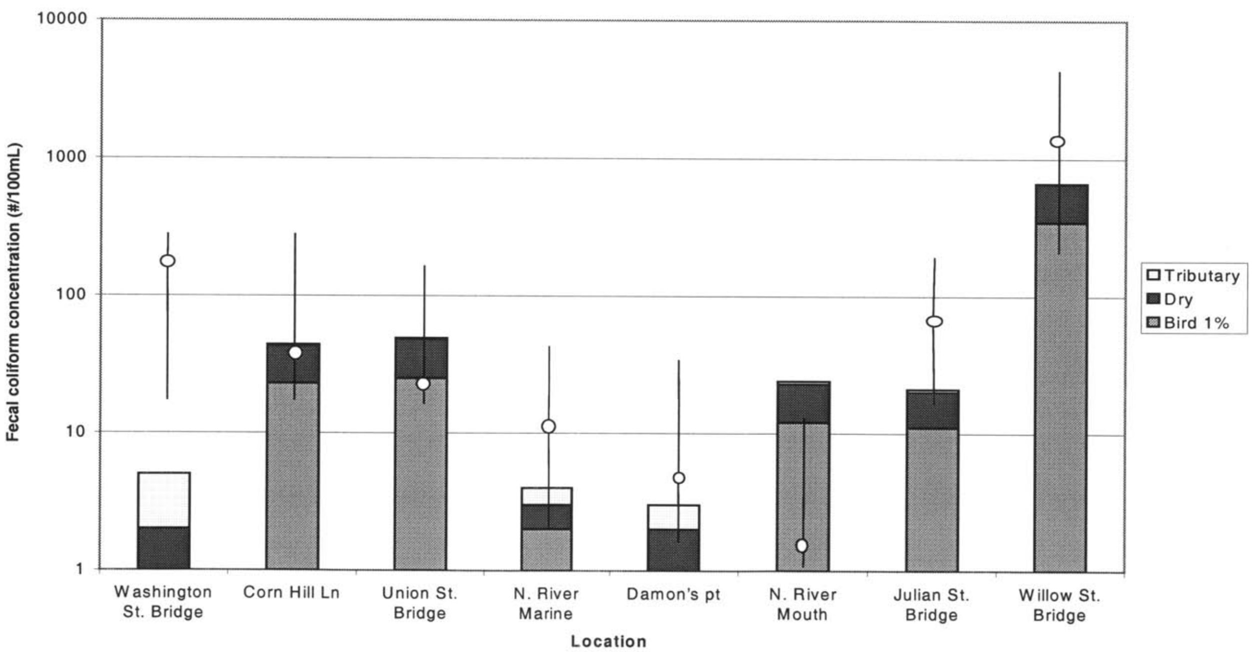



*Figure 9.7 Summary plot of receiving water fecal coliform concentrations at high tide due to dry-weather sources*

## 9.4 Wet-weather storm drain loading

Contributions of bacteria to the rivers via wet-weather storm drains are discussed in Chapter 7.4. For this scenario, a 2-hour storm with total accumulation of 0.1-inch of rain is simulated. For all available storm drain loading data, the measured input loading is changed to represent a 0.1-inch storm using the following formula:

$$\frac{\dot{m}_{\mathrm{mod}\,el}}{\dot{m}_{measured}} = \frac{0.1}{P} \tag{9.1}$$

where $\dot{m}_{\mathrm{mod}\,el}$ = loading input into the model

$\dot{m}_{measured}$ = loading input measured

P = amount of precipitation accompanying measured loading input (in.)

Wet-weather storm drain loadings ($\dot{m}_{measured}$) are obtained from various sources by multiplying the instantaneous flow rate and the fecal coliform concentration. The simulation begins at 17:03 and the storm begins with full force using Equation 9.1 at 19:03 for two hours until 21:03. After the first two hours had passed, the loading obtained from Equation 9.1 is reduced by half for another hour until 22:03. And finally, the original loading is reduced to a quarter ending at 23:03. This is performed to simulate the fact that not all the storm drain water travels to the rivers instantaneously. The simulations allow for 2 extra hours for the water to travel. Loadings from the various sources over the four hours are shown in Table 9.3. As in the case with dry-weather storm drain loading, all inputs are simulated as point sources.

*Table 9.3 Wet-weather fecal coliform input values*

| Location | Loading (#/sec) (19:03 - 21:03) | Loading (#/sec) (21:03-22:03) | Loading (#/sec) (22:03-23:03) | Source |
|---|---|---|---|---|
| Driftway | 2 | 1 | 0.5 | BSC (1987) |
| Damon's Point | 1 | 0.5 | 0.25 | BSC (1987) |
| Mary's Landing | 42 | 21 | 11 | BSC (1987) |
| Landing (Rte. 3A) | 1000 | 500 | 250 | BSC (1987) |
| River Circle | 1175 | 588 | 294 | BSC (1987) |
| Bridge St. | 79450 | 39725 | 19863 | BSC (1987) |
| Marshfield Ave. | 3161 | 1581 | 790 | BSC (1987) |
| Central Ave. | 420 | 210 | 105 | BSC (1987) |
| Julian St. | 1905 | 953 | 477 | SR SWI (1993) |
| Bridgewaye | 7560 | 3780 | 1890 | SR SWI (1993) |
| Sea St. | 15120 | 7560 | 3780 | SR SWI (1993) |
| Willow St. | 2469 | 12348 | 6174 | SR SWI (1993) |
| Union St. | 2633 | 1317 | 659 | BEC (1991) |
| King's Landing | 5663 | 2862 | 1431 | BEC (1991) |

Note: BEC (Baystate Environmental Consultants); BSC (The BSC Group); SR SWI (South River Storm water investigations)

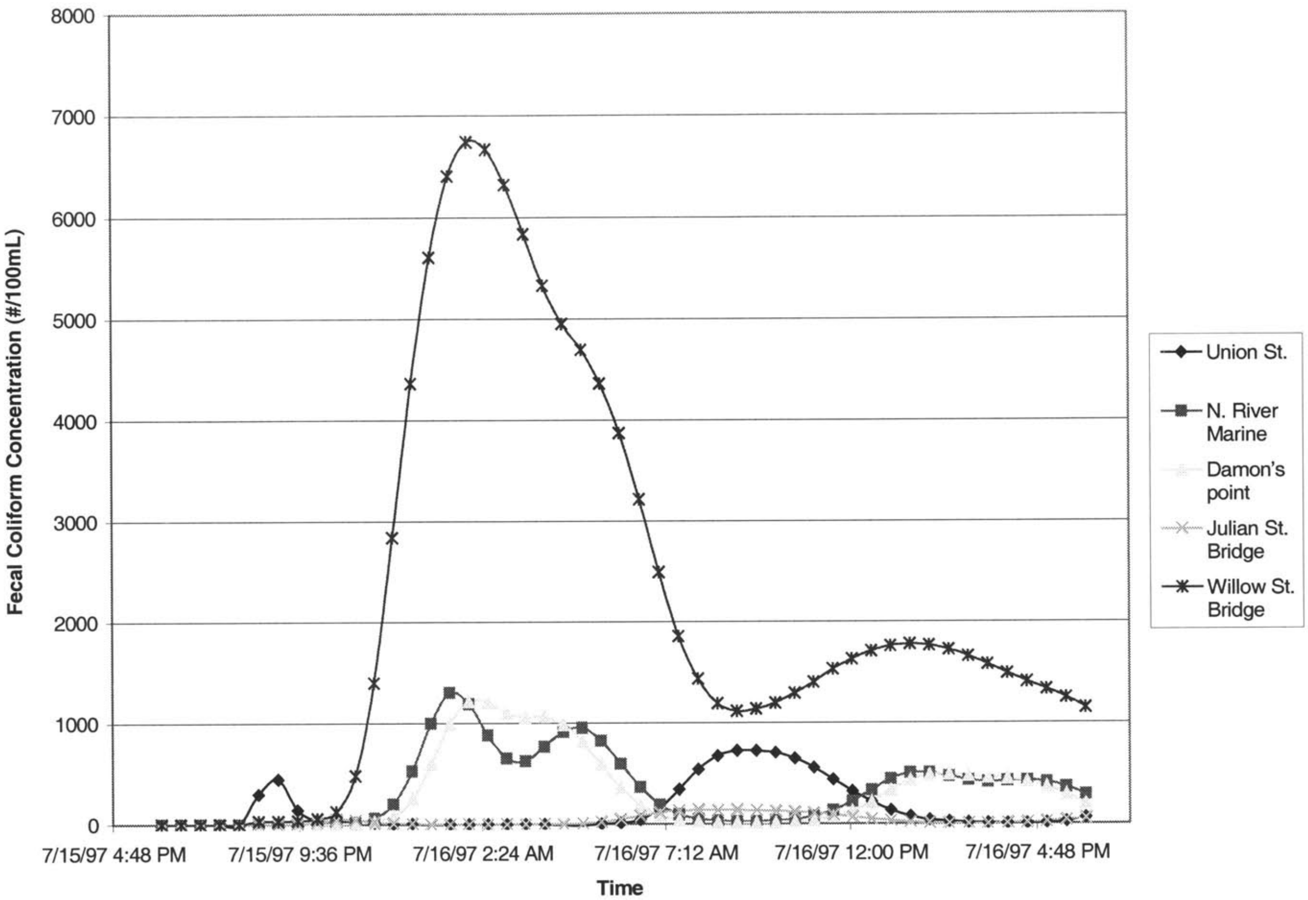



*Figure 9.8 Simulated fecal coliform concentration during wet-weather conditions*

Comparing wet-weather modeled scenario with actual data is not possible. Although it is known that wet-weather storm drains on the North and South Rivers have some adverse effects, a thorough investigation of the storm drains during wet-weather flow does not exist (Ivas, 1999). Currently, data are collected for the purpose of monitoring the rivers only. Furthermore, the simulated scenario is based on a fictitious storm and does not correspond with actual data. As shown in Figure 9.8, there are large fluctuations between different time periods. The times of day that actual samples are collected are almost never recorded making it even more difficult to make any meaningful comparisons.

Figure 9.9 shows the comparison between dry and wet-weather fecal coliform sources. The relative magnitudes of concentrations from wet-weather sources are significantly higher than those from dry-weather sources. The wet-weather concentrations are taken at

7:03, 12 hours after the initial storm event. The dry-weather values in Figure 9.9 are similar to those from Figure 9.7.

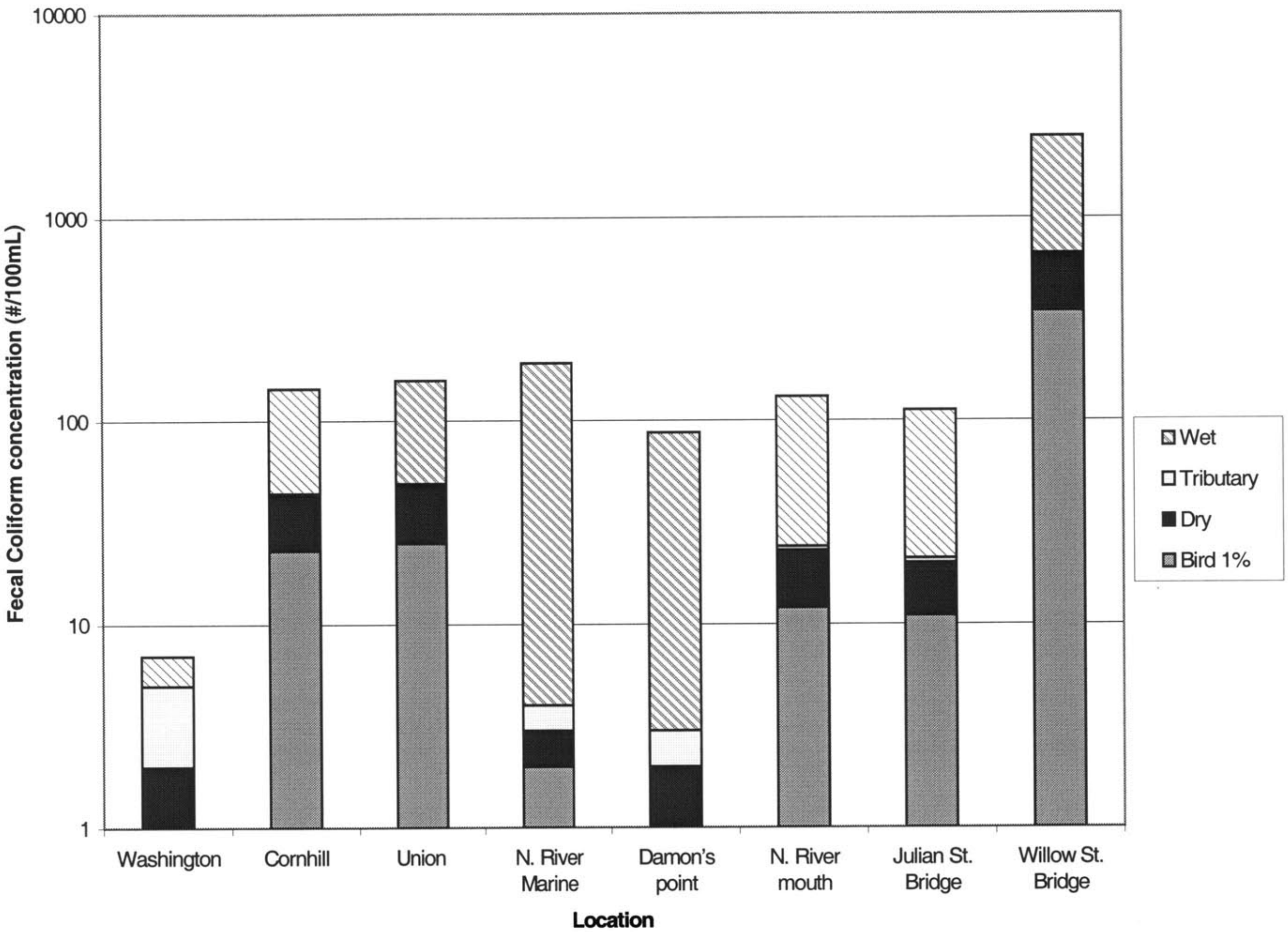



*Figure 9.9 Comparison of receiving water fecal coliform concentrations at high tide due to dry and wet-weather sources*

## 10. Conclusions and Recommendations

This initial application of the water quality model shows that it can be used to test the feasibility and effectiveness of future pollution abatement strategies. It can be used to test scenarios for possible future regional growth and urbanization. Furthermore, this model helps to identify vulnerable areas along the two rivers.

Of the four simulated fecal coliform loadings, tributary loadings have a minimal effect on the fecal coliform concentrations in the rivers whereas wet weather storm drain loadings contribute the most. Both dry weather storm drain and waterfowl loadings contribute significant amounts of contaminant into the rivers. However, the exact amount of constant dry-weather loads is still unknown. Future studies may involve the establishment of a dry-weather inverse model similar to the one performed for the Charles River watershed to determine the dry-weather loads (Socolofsky, 1997).

The development of an accurate fecal coliform model for the North and South Rivers would require accurate and consistent measurements by NSRWA. These measurements include sufficient fecal coliform loading data as well as data for model calibration.

To further develop the fecal coliform model, several specific recommendations are made:

1. In the summer months, precipitation in the North and South Rivers watershed differs greatly from Boston's. Hourly precipitation measurement within the watershed would help to determine the full impact of wet-weather loading.
2. Full storm surveys should be conducted in the summer months in both the rivers and at the sources.
3. Fecal coliform concentrations should be collected for all months of the year.
4. All storm drains should be carefully monitored to check for dry-weather flow. For drains with dry-weather flow, fecal coliform concentration as well as the amount of flow should be documented.
5. For all sampling, the time of day and stage of tide should be noted.

6. A study similar to that of Weiskel *et al.* would help quantify the specific fecal coliform loadings in the watershed. For example, field testing to determine the effects of on-lot disposal systems on the overall health of the rivers should be performed. As well, a waterfowl and boat loading study in the watershed would be helpful.
7. Consultations with other watershed associations with full range of volunteer sampling program such as the Charles River Watershed Association would be helpful (Munson, 1998).

## 11. References


Adams, E.E. 1999. *1.77 Water Quality Control.* MIT Subject Lecture Notes.

Baystate Environmental Consultants, Inc. 1991. *Pollution Source Assessment and Recommendations for Mitigation in the North River Watershed.* For the North and South Rivers Watershed Association.

Baystate Environmental Consultants, Inc. 1990. *Water Quality Assessment of the North River and its Tributaries.* For the North and South Rivers Watershed Association.

BSC Group 1987. *North River Water Quality Management Plan Final Report.* Prepared for North River Commission.

Brown, L.C. and T.O Barnwell Jr. 1987. *The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and Users Manual.* U.S. Environmental Protection Agency, Athens, GA., Report EPA/600/3-87/007.

Buchsbaum, R. and I. Valiela 1987. Variability in the chemistry of estuarine plants and its effect on feeding by Canada geese. *Oecologia.* Vol. 73 pp. 146-153.

Chapra, S.C. 1997. *Surface Water-Quality Modeling.* McGraw-Hill Co. Inc., New York.

Chen, M. 1988. Pollution of Ground water by Nutrients and Fecal Coliform from lakeshore septic tank systems. *Water, Air, and Soil Pollution* Vol. 37 pp. 407-417.

Churchill, N.T. 1999. DMF. Personal Communication. April 1999.

Churchill, N.T. 1994. Preliminary Shoreline Survey Report of South River in the towns of Marshfield and Scituate MB:6. Massachusetts Division of Marine Fisheries. July 25, 1994.

DFWELE 1998. Location of all pumpout stations in Massachusetts Coastal Waters. WWW at http://www.state.ma.us/dfwele/com/comcvahm.html.

DFWELE 1999. Department of Fisheries Wildlife and Environmental Law Enforcement. Personal Communication. April 1999.

Dickinson, E. 1998. Letter to U.S. Environmental Protection Agency. New England Division. http://www.boatus.com/gov/riban.htm.

Dickinson, E. 1999. Boat/U.S. Personal Communication. March 1999.

EPA 1999. NPDES Permit Tracking for Scituate WWTP. NPDES No. MA0102695. http://www.epa.gov/enviro/html/pcs/pcs_overview.html.

Gerba, C.P., Wallis, C., and Melnick, J.L. 1975. Fate of Wastewater bacteria and viruses in soil. *Journal of the irrigation and drainage division ASCE.* Vol. 101 September 1975 pp. 157-174.

Geyer, W.R. 1997. North River Dye Study Data (unpublished). Woods Hole Oceanographic Institute.

Geyer, W.R., and R.P. Signell 1992. A Reassessment of the Role of Tidal Dispersion in Estuaries and Bays. *Estuaries.* 15:97(12).

Hammer, M.J., Hammer Jr, M.J. 1996 *Water and Wastewater Technology.* Prentice Hall, New Jersey.

Hagedorn, C., Hansen, D.T., and Simonson, G.H. 1978 Survival and movement of fecla indicator bacteria in soil under conditions of saturated flow *Journal of Environemntal Quality.* Vol. 7 No. 1 pp. 55-59.

Ivas, S. 1999 NSRWA Personal Communication. April 1999.

King, I.P., 1993. *RMA-10: A Finite Element Model for Three-Dimensional Density Stratified Flow.* Environment Protection Authority, Bankstown, NSW, AWACS Interim Report 93/01/04.

King, I.P., 1997. *RMA-11: A Three Dimensional Finite Element Model for Water Quality in Estuaries and Streams*, University of California Department of Civil and Environmental Engineering, Davis, CA.

Tana, C.K. and Lee, S.S. 1999. North and South Rivers Modeling Project. Masters of Engineering project report. Department of Civil and Environmental Engineering. Massachusetts Institute of Technology. Cambridge, MA.

Mancini, J.L. 1978. Numerical estimates of coliform mortality rates under various conditions. Journal of WPCF pp. 2477-2484. November 1978.

MassGIS, 1995. Massachusetts Geographic Information System developed by Massachusetts Executive Office of Environmental Affairs (EOEA).

McAllister, T.L., Overton, M.F., and E.D. Brill, Jr. (1996) Cumulative Impact of Marinas on Estuarine Water Quality *Environmental Management* Vol. 20 No. 3 pp. 385-396.

MDMF (Massachusetts Division of Marine Fisheries) 1989 Shellfish Survey Data.

MDMF (Massachusetts Division of Marine Fisheries) 1994 Shellfish Survey Data.

Metcalf & Eddy. 1995. *Final Facilities Plan and Environmental Impact Report for Wastewater Management Volume I, II, and III* EOEA No. 5512, WPC-Mass.-887.

Morrill III, G. B. and L. G. Toler. 1973 Effect of septic-tank wastes on quality of water, Ipswich and Shawsheen River Basins, Massachusetts. *Journal Research of U.S. Geological Survey.* Vol. 1 No. 1 Jan-Feb 1973 pp. 117-120.

Munson, A. D. 1998. HSPF Modeling of the Charles River Watershed. Master of Science thesis. Massachusetts Institute of Technology. Cambridge, MA.

NOAA (National Oceanic and Atmospheric Administration) 1995 National Shellfish Register. WWW at www://state_of_coast.noaa.gov

NSRWA (North and South River Watershed Association) *1997-1998 NSRWA RiverWatch Data.*

NSRWA 1993 South River Storm Water Investigations.

Palmer, M.D.1983 Fecal coliform loadings from birds on bridges. *Canadian Journal of Civil Engineering.* Vol. 10 pp. 241-247.

Palmer, M. 1988 Bacterial loadings from resuspended sediments in recreational beaches. *Canadian Journal of Civil Engineering.* Vol. 15 pp. 450-455.

Reneau, Jr., R.B., Elder, Jr., J.H., Pettry, D.E., and Weston, C.W. 1975. Influence of soils on bacterial contamination of a watershed from septic sources. *Journal of Environmental Quality* Vol. 4 No. 2 pp. 249-252.

Socolofsky, S. A. 1997. Hydrologic and Bacteria Modeling of the Upper Charles River Watershed using HSPF. Master of Science thesis. Massachusetts Institute of Technology. Cambridge, MA.

Tana, C.K. 1999. A hydrodynamic model of the North and South River Estuary using RMA-10. Master of Engineering thesis. Massachusetts Institute of Technology. Cambridge, MA.

Thomann, R.V. and J.A. Mueller 1987. *Principles of Surface Water Quality Modeling and Control.* Harper & Row, New York.

Thatcher, M.L. 1999. Personal Communication. April 1999.

U.S. Fish and Wildlife Service 1992. National Recreational Boating Survey: Sanitation Pumpout Questionnaire Tabulation. January 1992.

Viraraghavan, T. 1978. Travel of microorganisms from a septic tile. *Water, Air, and Soil Pollution* Vol. 9 pp. 355-362.

Weiskel, P.K., B.L. Howes, and G.R. Heufelder 1996. Coliform Contamination of a Coastal Embayment: Sources and Transport Pathways. *Environmental Science and Technology.* Vol. 30 No.6 1872(10).

## Appendix A. Acronyms

| | |
|---|---|
| BEC | Baystate Environmental Consultants |
| BSC | The BSC Group |
| DEP | Massachusetts Department of Environmental Protection |
| DMF | Massachusetts Division of Marine Fisheries |
| DFWELE | Massachusetts Department of Fisheries, Wildlife and Environmental Law Enforcement |
| EPA | Environmental Protection Agency |
| FWPCA | Federal Water Pollution Control Act |
| FC | Fecal Coliform |
| M&E | Metcalf and Eddy |
| MGD | Million gallons per day |
| MSD | Marine Sanitation Device |
| NOAA | National Oceanic and Atmospheric Administration |
| NDPES | National Pollutant Discharge Elimination System |
| NSRWA | North and South River Watershed Association |
| PCS | Permit Compliance System |
| WHOI | Woods Hole Oceanographic Institute |
| WWTP | Wastewater Treatment Plant |

# Appendix B. Fecal Coliform Data

*Table B.1 Fecal coliform concentration (#/100mL) from NSRWA RiverWatch program*

| Date | Washington St. Bridge | Corn Hill Ln | Union St. Bridge | Scituate overflow pipe | Scituate WWTP | James Landing Marina | Rainfall (in.) |
|---|---|---|---|---|---|---|---|
| 7/1/97 | 150 | 63 | 24 | 20000 | TNTC | 12 | 0 |
| 7/9/97 | 48 | 61 | 38 | 25 | 45 | 22 | 0.02 |
| 7/15/97 | 300 | 22 | 13 | 300 | 166 | 21 | 0 |
| 7/24/97 | 130 | * | 11 | 200 | 130 | 15 | 0 |
| 7/29/97 | 300 | 31 | 24 | 29 | 35 | 21 | 0.03 |
| 8/7/97 | 300 | 45 | 28 | 130 | 279 | 22 | 0.02 |
| 8/12/97 | 190 | 49 | 29 | 180 | 177 | 7 | 0.03 |
| 8/21/97 | 500 | 44 | 35 | 600 | 529 | 33 | 0.25 |
| 8/26/97 | 100 | 77 | 26 | 48 | 93 | 3 | 0 |
| 7/6/98 | 73 | 260 | 210 | 33 | | 77 | 0.3 |
| 7/14/98 | 300 | 72 | 35 | 27 | | 58 | 0 |
| 7/20/98 | 230 | 400 | 190 | 87 | | 35 | 0 |
| 7/28/98 | 140 | 29 | 14 | 130 | | 10 | 0 |
| 8/3/98 | 130 | 110 | 37 | 85 | | 21 | 0 |
| 8/13/98 | 800 | 1200 | 230 | 130 | | 700 | 1.34 |
| 8/17/98 | 420 | 170 | 75 | 43 | | 66 | 0 |
| 8/27/98 | 98 | 79 | 64 | 170 | | 5 | 0.29 |
| 8/31/98 | 250 | 260 | 180 | 24 | | 27 | 0.05 |

| Date | N. River Marine | Damon's pt | N. River Mouth | Julian St. Bridge | Willow St. Bridge | Rainfall (in.) |
|---|---|---|---|---|---|---|
| 7/1/97 | 2 | 1 | 1 | 83 | 1400 | 0 |
| 7/9/97 | 14 | 2 | 1 | 53 | 1200 | 0.02 |
| 7/15/97 | 5 | 2 | 1 | 50 | 1400 | 0 |
| 7/24/97 | 4 | 4 | 0 | 51 | 1100 | 0 |
| 7/29/97 | 4 | 6 | 2 | 64 | 500 | 0.03 |
| 8/7/97 | 10 | 11 | 6 | 83 | 2500 | 0.02 |
| 8/12/97 | 8 | 6 | 2 | 24 | 800 | 0.03 |
| 8/21/97 | 21 | 8 | 9 | 68 | 700 | 0.25 |
| 8/26/97 | 15 | 7 | 2 | 120 | 900 | 0 |
| 7/6/98 | 53 | 54 | 10 | 400 | 58 | 0.3 |
| 7/14/98 | 34 | 30 | 8 | 130 | 400 | 0 |
| 7/20/98 | 16 | 25 | 7 | 250 | 4900 | 0 |
| 7/28/98 | 11 | 4 | 2 | 61 | 1000 | 0 |
| 8/3/98 | 9 | 7 | 1 | 30 | 1900 | 0 |
| 8/13/98 | 140 | 110 | 26 | 150 | 1000 | 1.34 |
| 8/17/98 | 35 | 29 | 11 | 300 | 1800 | 0 |
| 8/27/98 | 18 | 21 | 54 | 110 | 400 | 0.29 |
| 8/31/98 | 34 | 37 | 20 | 130 | 400 | 0.05 |

*Table B.2 Fecal coliform data from Division of Marine Fisheries*

| Date | Location | Time (min) | Tidal stage | Salinity (ppt) | FC (#/100mL) | Activity type | Activity amount |
|---|---|---|---|---|---|---|---|
| 2/5/87 | Trouant Is. | 560 | Ebb Top Half | 27 | 11 | Water fowl | 1000 |
| 7/1/87 | Trouant Is. | 575 | Ebb Top Half | 25 | 5.8 | Water fowl | 350 |
| 11/16/88 | Trouant Is. | 505 | Ebb Top Half | 25.2 | 5.8 | Boats | 3 |
| 1/31/89 | Trouant Is. | 598 | Ebb Top Half | 28.5 | 1.7 | Water fowl | 30 |
| 2/14/89 | Trouant Is. | 610 | Ebb Top Half | 25.9 | 0.85 | Water fowl | 300 |
| 3/2/89 | Trouant Is. | 614 | Ebb Top Half | 25.2 | 0.85 | Boats | 3 |
| 4/12/89 | Trouant Is. | 628 | Ebb Top Half | 22 | 0.85 | Water fowl | 20 |
| 2/14/90 | Trouant Is. | 417 | Ebb Top Half | 30 | 8.2 | Water fowl | 11 |
| 2/21/90 | Trouant Is. | 780 | Ebb Top Half | 28 | 0.85 | Water fowl | 100 |
| 10/25/90 | Trouant Is. | 573 | Ebb Top Half | 30 | 65 | Boats | 25 |
| 11/8/90 | Trouant Is. | 520 | Ebb Top Half | 30 | 8.2 | Water fowl | 300 |
| 3/6/91 | Trouant Is. | 532 | Ebb Top Half | 25 | 41 | Water fowl | 100 |
| 8/8/93 | Trouant Is. | 1095 | Ebb Top Half | 29 | 247 | Boats | 3 |
| 5/16/94 | Trouant Is. | 574 | Ebb Top Half | 25 | 30 | Water fowl | 3 |
| 6/7/94 | Trouant Is. | 749 | Ebb Top Half | 32 | 9.9 | Water fowl | 30 |
| 6/22/94 | Trouant Is. | 673 | Ebb Top Half | 31 | 1.7 | Water fowl | 2 |
| 6/27/94 | Trouant Is. | 540 | Ebb Top Half | 31 | 30 | Boats | 2 |
| 6/30/94 | Trouant Is. | 600 | Ebb Top Half | 32 | 3.6 | Boats | 1 |
| 7/6/94 | Trouant Is. | 765 | Ebb Top Half | 32 | 8.9 | Boats | 1 |
| 7/18/94 | Trouant Is. | 765 | Ebb Top Half | 32 | 9.9 | Water fowl | 4 |
| 8/1/94 | Trouant Is. | 674 | Ebb Top Half | 32 | 1.6 | Water fowl | 12 |
| 8/8/93 | Broadway Creek | 1110 | Ebb Top Half | 28 | 247 | Water fowl | 10 |
| 11/16/88 | On Map | 509 | ? | 25.2 | 5.8 | Water fowl | 12 |
| 11/30/88 | On Map | 604 | Ebb Top Half | 25.2 | 14 | Water fowl | 2 |
| 11/16/88 | 224 Central | 518 | Ebb Top Half | 23.9 | 18 | Water fowl | 10 |
| 1/31/89 | 224 Central | 556 | Ebb Top Half | 26.5 | 0.85 | Water fowl | 50 |
| 2/14/89 | 224 Central | 577 | Ebb Top Half | 25.2 | 5.8 | Water fowl | 35 |
| 3/2/89 | 224 Central | 675 | Ebb Top Half | 23.3 | 3.6 | Boats | 1 |
| 6/7/89 | 224 Central | 609 | Low | 15 | 64 | Boats | 2 |
| 11/29/89 | 224 Central | 774 | Ebb Top Half | 32 | 0.85 | Boats | 2 |
| 2/8/90 | 224 Central | 733 | Ebb Top Half | 30 | 0.85 | Boats | 1 |
| 2/14/90 | 224 Central | 437 | Ebb Top Half | 26 | 18 | Water fowl | 13 |
| 10/25/90 | 224 Central | 563 | Ebb Top Half | 27 | 65 | Boats | 2 |
| 11/8/90 | 224 Central | 507 | Ebb Top Half | 30 | 23 | Boats | 4 |
| 3/6/91 | 224 Central | 519 | Ebb Top Half | 20 | 55 | Boats | 1 |
| 8/8/93 | 224 Central | 1127 | Ebb Top Half | 22 | 247 | Boats | 2 |
| 5/16/94 | 224 Central | 584 | Ebb Top Half | 24 | 41 | Boats | 1 |
| 6/7/94 | 224 Central | 730 | Ebb Top Half | 29 | 9.9 | Boats | 1 |
| 6/22/94 | 224 Central | 667 | Ebb Top Half | 31 | 1.6 | Boats | 2 |
| 6/27/94 | 224 Central | 526 | Ebb Top Half | 30 | 65 | Boats | 2 |
| 6/30/94 | 224 Central | 594 | Ebb Top Half | 30 | 65 | Boats | 3 |
| 7/6/94 | 224 Central | 759 | Ebb Top Half | 32 | 8.9 | Boats | 1 |
| 7/18/94 | 224 Central | 769 | Ebb Top Half | 31 | 30 | Boats | 4 |
| 8/1/94 | 224 Central | 685 | Ebb Top Half | 30 | 11 | Boats | 1 |
| 2/10/88 | Seaview Ave | 515 | Ebb Top Half | 23.3 | 23 | Animals | 50 |
| 1/31/89 | Seaview Ave | 552 | Ebb Top Half | 25.9 | 14 | Water fowl | 75 |

| Date | Location | Time (min) | Tidal stage | Salinity (ppt) | FC (#/100mL) | Activity type | Activity amount |
|---|---|---|---|---|---|---|---|
| 3/2/89 | Seaview Ave | 668 | Ebb Top Half | 23.3 | 14 | Water fowl | 20 |
| 2/14/90 | Seaview Ave | 440 | Ebb Top Half | 27 | 64 | Water fowl | 17 |
| 11/8/90 | Seaview Ave | 504 | Ebb Top Half | 31 | 11 | Water fowl | 4 |
| 5/16/94 | Seaview Ave | 587 | Ebb Top Half | 27 | 8.2 | Boats | 1 |
| 6/7/94 | Seaview Ave | 725 | Ebb Top Half | 29 | 9.9 | Boats | 1 |
| 6/22/94 | Seaview Ave | 664 | Ebb Top Half | 31 | 1.7 | Boats | 2 |
| 7/6/94 | Seaview Ave | 754 | Ebb Top Half | 32 | 8.9 | Boats | 3 |
| 7/18/94 | Seaview Ave | 772 | Ebb Top Half | 31 | 40 | Water fowl | 2 |
| 8/8/93 | End of Grandview | 1139 | Ebb Top Half | 25 | 247 | Boats | 6 |
| 6/7/93 | End of Grandview | 763 | Ebb Top Half | 32 | 9.9 | Boats | 5 |
| 6/22/94 | End of Grandview | 659 | Ebb Top Half | 31 | 1.7 | Boats | 12 |
| 6/30/94 | End of Grandview | 620 | Ebb Top Half | 27 | 65 | Boats | 4 |
| 7/6/94 | End of Grandview | 787 | Ebb Top Half | 31 | 18 | Boats | 4 |
| 7/18/94 | End of Grandview | 795 | Ebb Top Half | 30 | 20 | Boats | 5 |
| 8/1/94 | End of Grandview | 655 | Ebb Top Half | 30 | 18 | Boats | 7 |
| 8/8/93 | Marshfield Ave Bridge | 1154 | Ebb Top Half | 24 | 247 | Boats | 4 |
| 6/7/94 | Marshfield Ave Bridge | 720 | Ebb Top Half | 30 | 9.9 | Boats | 22 |
| 6/22/94 | Marshfield Ave Bridge | 653 | Ebb Top Half | 31 | 18 | Boats | 35 |
| 6/27/94 | Marshfield Ave Bridge | 547 | Ebb Top Half | 29 | 64 | Boats | 51 |
| 6/30/94 | Marshfield Ave Bridge | 609 | Ebb Top Half | 26 | 65 | Boats | 50 |
| 7/6/94 | Marshfield Ave Bridge | 780 | Ebb Top Half | 31 | 8.9 | Boats | 6 |
| 7/18/94 | Marshfield Ave Bridge | 779 | Ebb Top Half | 30 | 60 | Boats | 50 |
| 8/1/94 | Marshfield Ave Bridge | 660 | Ebb Top Half | 28 | 65 | Boats | 56 |
| 6/7/94 | Julian St. Bridge | 710 | High | 30 | 9.9 | Water fowl | 3 |
| 7/6/94 | Julian St. Bridge | 749 | Ebb Top Half | 31 | 18 | People | 4 |
| 1/31/89 | USAF Base | 560 | Ebb Top Half | 28.5 | 5.8 | Water fowl | 50 |

*Table B.3 Fecal coliform data from the BEC report*

| **Subwatershed** | **Flow (cfs)** | | | **Fecal Coliform (#/100mL)** | | |
|---|---|---|---|---|---|---|
| | **Low** | **Typical** | **High** | **Low** | **Typical** | **High** |
| Indian Head Creek/River | 16.2 | 56.8 | 129.9 | 2 | 33 | 620 |
| herring Brook | 7 | 24.5 | 56 | 1 | 36 | 220 |
| East Upper Third Herring Brook | 2.1 | 7.4 | 16.9 | 5 | 36 | 100 |
| West Upper Third Herring Brook | 2.1 | 7.5 | 17.1 | 13 | 66 | 180 |
| Lower Third herring Brook | 5.3 | 18.4 | 42.1 | 1 | 84 | 2200 |
| Upper North River | 29 | 101.3 | 231.6 | 1 | 54 | 500 |
| Barque Hill Area | 0.2 | 0.9 | 2 | 3 | 172 | 3200 |
| Robinson Creek | 0.8 | 2.9 | 6.7 | 30 | 125 | 550 |
| Route 3 Area | 30.6 | 107.1 | 244.9 | 10 | 175 | 1300 |
| Mounce Brook | 1.1 | 3.8 | 8.6 | 1 | 25 | 540 |
| Twomile Cemetery Area | 32.2 | 112.5 | 257.2 | 20 | 150 | 500 |
| Dwelleys Creek | 0.6 | 2 | 4.5 | 20 | 53 | 2700 |
| Second Herring Brook | 2 | 7 | 16 | 10 | 235 | 1700 |
| Corn Hill Area | 35.3 | 123.4 | 282 | 20 | 156 | 1700 |
| Union Street Area | 0.1 | 0.3 | 0.7 | 31 | 10217 | 190000 |
| Bridge Street Area | 0 | 0.1 | 0.3 | 16 | 866 | 14000 |
| Kings Landing Area | 0 | 0.2 | 0.3 | 100 | 1000 | 10000 |
| Old First Parish Area | 35.7 | 125 | 285.7 | 10 | 57 | 176 |
| Stony Brook | 0.4 | 1.3 | 3 | 1 | 49 | 1200 |
| Cove Brook | 0.7 | 2.5 | 5.6 | 10 | 76 | 2000 |
| Riverside Circle Area | 0 | 0.1 | 0.3 | 1 | 148 | 27000 |
| Route 3A Pipe Area | 0 | 0 | 0.1 | 5 | 34 | 3850 |
| Lower North River | 37.1 | 129.9 | 296.9 | 1 | 25 | 500 |

## Appendix C. Governing equations for fecal coliform decay

In RMA-11, fecal coliform transport is modeled using three loss parameters: settling, decay in darkness, and light sensitive decay (King, 1997).

The loss rate for fecal coliform bacteria ($G_c$ ) can be represented as

$$G_c = -(K_{c1} + K_{c2} + K_{c3}/d)\, C_c$$

where

| | | |
|---|---|---|
| $C_c$ | = | the concentration of coliform, (# of fecal coliforms/100mL) |
| $K_{c1}$ | = | coliform die off rate in darkness - temperature adjusted (1/hr) |
| $K_{c2}$ | = | coliform die off rate due to light - temperature adjusted (1/hr) |
| $K_{c3}$ | = | coliform settling rate - temperature adjusted (m/hr). |
| $d^{++}$ | = | depth of water body |

### C.1 Coliform die-off rate in darkness

The coliform rate parameters are input into RMA-11 in terms of $T_{90}$. $T_{90}$ is the time (hours) for 90% of the fecal coliform to die off. To calculate coliform die off rate in darkness, the equation is given by:

$$K_{c1} = \frac{2.3}{T_{90}} \tag{C.1}$$

### C.2 Coliform die-off rate due to light

The loss from the effect of light, $K_{c2}$, depends the light intensity, light extinction coefficient, coliform light coefficient, and water depth. The following equation is valid for depth-averaged cases:

$$K_{c2} = 2.3026 \frac{\left[ L_i \frac{(1-\exp(-\lambda d))}{(\lambda d)} \right]^{0.7}}{L_c} \qquad \text{(C.2)}$$

where

| | | |
|---|---|---|
| $L_i$ | = | light intensity ($MJ/M^2/hr$) |
| $L_c$ | = | coliform light coefficient ($hr[MJ/m^2/hr]^{0.7}$) |
| $\lambda$ | = | light extinction coefficient (1/m) |
| d | = | water depth (m) |

As in the case in Chapter 8.1, coliform die off rates due to light are input into RMA-11 in terms of $T_{90}$. Therefore, $K_{c2}$ is represented as:

$$K_{c2} = \frac{2.3}{T90_{light}} \qquad \text{(C.3)}$$

But,

$$T90_{light} = \frac{L_{coef}}{I(z)^{0.7}} \qquad \text{(C.4)}$$

where $L_{coef}$ = light coefficient
$I(z)$ = light intensity as a function of depth, z

To determine I(z) at particular depths, the equation is given by:

$$I(z) = I_o(1 - \exp(-\lambda z)) \qquad \text{(C.5)}$$

The required input values for RMA-11 in this Chapter are the light coefficient ($L_{coef}$) and the light extinction coefficient ($\lambda$). Light intensity at the surface of the water, $I_o$ is obtained from other computations within RMA-11.

### C.3 Coliform settling rate

Settling loss depends on the quantity of organisms attached to particles, the settling velocity and the depth of the river. The user directly enters this settling rate, $K_{c3}$, in (m/hr) into RMA-11.

# Appendix D. Sample RMA-11 Input files

## D.1 Calibration runs

### *File: bothdye3.r11*

```
OUTFIL   bothdye3.2o
R4QFIL   bothdye3.r4q
OUTSPL   bothdye3.SPL
INBNRST bothdye2.rst
OUTBNRSTbothdye3.rst
VELBNFILboth2dt3.res
INBNGEO both2dt.geo
BCFIL    bothdye3.alt
OUTBNRESbothdye3.res
ENDFIL
TI          Rocky's dye study (1st release)
C0          1997    196.   10.05
C1             1       2       0       1       0       0       1       1       1
C2         2.461     831    1107      1.      1.      1.      1.    0.05
C3             6       0     360    -360       1       0       0       0       0
C4            0.      0.     0.0      0.      0.      0.
SP             1    1694    1676    1642    1636    1617    1605    1578    1564
DF             1    0.45    0.45    0.02     0.1     0.1
DF             2    0.45    0.45    0.02     0.1     0.1
DF             3    0.45    0.45    0.02     0.1     0.1
CC1          323     324
CC1         2510    2511    2512
CC1         1882    1883
CC1         1082    1083
CC1          289     473
CC1          538     541
CC1          307     409
CC1          924     931
CC1          550     595
CC1          472     605
CC1          606     607
CC1          608     609
CC1          610     666
CC1          669     683
CC1         1034    1036    1038
ENDGEO
ENDINIT
DT          0.05
ENDSTEP
ENDDATA
```

### *File: bothdye3.spl*

```
DT          0.05
ENDSTEP
ENDDATA
```

*File: bothdye3.r4q*

```
Dye Test
CONSTITUENT LIST
    5    10    15    20    25    30    35    40    45    50    55    60    65    70    75   80
Type      1
Pass     -1
Conv  0.01
GLOBAL MODEL PARAMETERS
       8       16       24       32       40       48       56       64       72       80
SYSTEM      2.461    42.17   -70.72     -75.              1997        1
ARBCON1A      dye        0        0        0        0        0        0        0        0
ARBCON1B       10       1.       0.       0.       0.       0.       0.       0.        0
ELEMENT VARIABLE PARAMETERS - ONE SET FOR EACH ELEMENT TYPE
       8       16       24       32       40       48       56       64       72       80
ELEMTYPE        1
ARBCON1         0        0        0      0.0        0        0        0        0        0
ENDELEM
ELEMTYPE        2
ARBCON1         0        0        0      0.0        0        0        0        0        0
ENDELEM
ELEMTYPE        3
ARBCON1         0        0        0      0.0        0        0        0        0        0
ENDELEM
ENDDATA
```

## D.2 Dry-weather storm drain loading and tributary inputs

### *File: bothfc3.r11*

```
OUTFIL   bothfc3.2o
R4QFIL   bothfc3.r4q
OUTSPL   bothfc3.SPL
OUTRST   bothfc3.rst
VELBNFILboth2dp2.res
INBNGEO both2di.geo
BCFIL    bothfc3.alt
OUTBNRESbothfc3.res
ENDFIL
TI         All tributaries with boundary conditions and storm drains (dry)
C0           1997     195.   17.05
C1              1        2       0       0       0       0       1       0       1
C2          2.461      831    1107      1.      1.      1.      1.
C3              6        0      50     -50       1       0       0       0       0
C4             0.       0.     0.0      0.      0.      0.
SP              1     2336    1515    1596    1799    2632     965    2039    2404
DF              1     0.45     0.1    0.02     0.1     0.1
DF              2     0.45     1.0    0.02     0.1     0.1
DF              3     0.45     0.1    0.02     0.1     0.1
CC1           323      324
CC1          2510     2511    2512
CC1          1882     1883
CC1          1082     1083
CC1           289      473
CC1           538      541
CC1           307      409
CC1           924      931
CC1           550      595
CC1           472      605
CC1           606      607
CC1           608      609
CC1           610      666
CC1           669      683
CC1          1034     1036    1038
ENDGEO
IC              0       0.
ENDINIT
DT           0.50
BC              1      33.
BC              3     276.
BC              4      20.
BC              5     235.
BC              6      84.
BC              7      36.
BC              8      1.3
BC             10      76.
BC             11      49.
BC             12      53.
BC             14      14.
NL            154              878.
NL            360             200.0
NL            254               9.0
NL            210               90.
NL            374              25.0
NL            359              173.
NL           1877             2268.
ENDSTEP
```

```
ENDDATA
```

### *File: bothfc3.alt*

```
DT           0.50
BC              1      33.
BC              3     276.
BC              4      20.
BC              5     235.
BC              6      84.
BC              7      36.
BC              8      1.3
BC             10      76.
BC             11      49.
BC             12      53.
BC             13       9.
BC             14      14.
NL            154             878.
NL            360             200.
NL            254              9.0
NL            210              90.
NL            374             25.0
NL            359             173.
NL           1877            2268.
ENDSTEP
ENDDATA
```

### *File: bothfc3.r4q*

```
Fecal Coliform Test - all tributaries with boundary conditions
CONSTITUENT LIST
    5   10   15   20   25   30   35   40   45   50   55   60   65   70   75
80
Type    15
Pass    -1
Conv  0.01
GLOBAL MODEL PARAMETERS
       8       16       24       32       40       48       56       64       72
80
SYSTEM     2.461   42.17  -70.72    -75.            1997        1
COLIF        1.0     1.0
ELEMENT VARIABLE PARAMETERS - ONE SET FOR EACH ELEMENT TYPE
       8       16       24       32       40       48       56       64       72
80
ELEMTYPE       1
COLIF        2.5      0.      0.      0.
ENDELEM
ELEMTYPE       2
COLIF        2.5      0.      0.      0.
ENDELEM
ELEMTYPE       3
COLIF        2.5      0.      0.      0.
ENDELEM
ENDDATA
```